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Assessing Consequential Scenarios in a Complex Operational Environment Using Agent-Based Simulation

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NOTICES

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14. ABSTRACT

In an operational environment characterized by interactive complexity, emergence, and near constant change, this report examines whether agent-based or game-theoretic capability can improve the military decision-making process by providing additional rigor, speed, or flexibility during tactical US Army wargaming. The report considers methodologies to improve analysis of the human domain, identifies frameworks for modeling such a capability, and compares them against current Army wargaming practices. The report is composed of 5 sections: State of Wargaming, Agent-Based Modeling in Tactical Wargaming, Modeling Human–Computer Decision-Making, Existing Research and Applied Development of Agent-Based Modeling, and Plan for Research Development, Technology, and Training. The report concludes with a recommended technology and research path for the Army.

15. SUBJECT TERMS

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Executive Summary

Operational art—the creative thinking used to design strategies, campaigns, and major operations and to organize and employ military force—allows commanders to understand challenges facing them and to conceptualize approaches for achieving the nation's strategic objectives. This study asks the question, Could the art of mission planning and campaign design, where critical and creative thinking are used to understand the fundamental nature of a complex military problem, benefit from new opportunities provided by mathematics and science? That is, might recent advancements in computational social science, agent-based modeling (ABM) and simulations, and complex adaptive systems offer commanders and their planning staffs new opportunities to do the following:

1) Rigorously explore and make sense of interactively complex operational environments.
2) Unveil the nature of ill-structured military problems.
3) Move beyond logical limitations of linear, reductionist methods used in the intelligence preparation of the battlefield (IPB).

Future warfare will likely remain characterized by uncertainty. Politicians will send US forces to war while having varying depths of understanding of the specific complex factors contributing to violence, fear, and depravity. Commanders, their planning staffs, and intelligence analysts will encounter military problems that exist in 4 different knowledge states, simultaneously: known, knowable, complex, and chaotic.

Known*:* The behavior of a uniformed enemy is somewhat predictable because it is based on doctrine, movement rates, and the limitations of weapon systems and on the interaction of system components that are not individually purposeful. This state is amenable to the present-day IPB.

Knowable*:* Cause and effect can be discerned over time using wide area surveillance, pattern of life techniques, big data collection and mining, or simply by talking to the right people at the right time.

Complex*:* Interactive military problems run the risk of oversimplification in Washington, DC and at higher levels of command. Interactive emergence creates unpredictable situations, and solutions to murky problems may have totally unexpected consequences.

Chaotic: Systems suggest that greater complexity induces less-predictable emergent behavior. There is no presumption of rational choice, of order, or of a unitary and stable threat.

This study evaluates the capabilities of agent-based analytics and game theory with the goal of identifying potential investment areas for US Army Science and Technology (S&T) targeted for research and development relative to automated and semi-automated analysis. For its purposes, the authors examined ABM as a means to improve wargaming rigor and minimize decision-making risk in the Human Domain, specifically through its application to tactical battalion-, brigade-, and division-level wargaming.

Study Composition

This report is composed of 5 sections: 1) State of Wargaming, 2) Agent-Based Modeling in Tactical Wargaming, 3) Modeling Human–Computer Decision-Making, 4) Existing Research and Applied Development of Agent-Based Modeling, and 5) Plan for Research Development, Technology, and Training.

State of Wargaming begins with a summarization of Army wargaming, followed by an introduction to the history of wargaming applications. This section identifies analytical frameworks the Army uses to communicate strategic and operational situational understandings to tactical commanders and identifies challenges to current Army wargaming practices.

Agent-Based Modeling in Tactical Wargaming introduces the concept of ABM, especially with respect to the Human Domain. It explores the potential application of ABM to tactical wargaming, examining how it can improve the rigor of the current wargaming process.

Model Human–Computer Decision-Making begins with a survey of artificial intelligence and explores how ABM relates to broader artificial intelligence capabilities. This chapter discusses several decision-making frameworks, working from the assumption that decision-making is a traditional human-cognitive process and artificial intelligence is a capability that can assist the human. It then discusses agent-based design principles and patterns, in which each agent embodies their own decision-making capabilities.

Existing Research and Applied Development of Agent-Based Modeling reviews current state-of-the-art ABM capabilities, exploring tools that exhibit agent-based capabilities, identifying a framework for determining the maturity of such research, and reviewing how current agent-based research could assist the Army in creating a future tactical wargaming capability.

Plan for Research Development, Technology, and Training presents the study recommendations, beginning with a holistic Army perspective, then addressing specific technologies and capabilities and identifying training and education recommendations, specific to the implementation of agent-based capabilities.

Recommendation

The study makes 4 recommendations: 1) begin research and development of an Army-centric ABM capability, 2) form a stateside repository, 3) implement an ABM capability as a multilayered, distributed application, and 4) provide applicable training to ensure appropriate and knowledgeable proficiency. The authors recommend that a combination of each of the aforementioned is essential to the success of the Army mission. Furthermore, the risk of not having a tactical ABM wargaming capability in the future would be greater than the status quo.

The first recommendation, that the Army S&T community begins researching and developing Army-centric agent-based models, comprises 4 subelements: 1) research and development of resources that model tactical Human Domain attributes, 2) research and development of automated reasoning processes that support rigorous analysis, 3) research and development of a cognitive-social framework, and 4) evaluation of resources and models in terms of a model maturity framework. The study identifies short-, medium-, and long-term research goals for each of these elements.

As stated earlier, the second recommendation is to form and maintain a stateside repository of worldwide applicable models, agents, and resources; that is, a so-called Army Wargaming Intelligence Center. The authors base this recommendation on "Request for Support" functionality that the Joint Improvised Threat Defeat Agency's Counter-Improvised Explosive Device Operations/Intelligence Center supported with its "Attack the Network" operations. The recommendation particularly intends the development of a system and set of processes and personnel who support timely (e.g., 6 h, 24 h, 14 days, etc.) requests for information while interacting with liaisons representing a whole-of-government to coordinate wargamed courses of action.

To implement the third recommendation, the Army agent-based capability as a multilayered and distributed application, the authors recommend that the Army require the user interface implementation to be a web-based application, compatible with the Distributed Common Ground System–Army Program of Record. However, in light of possible network disconnections at the tactical level, the web-based application would need to run as a standalone, hybrid web application on a client machine.

The fourth recommendation involves incorporating applied topics of culture, tribes, complex adaptive systems, game theory, and applied statistics into specialized education and training curriculums, such as those provided at the Command and General Staff College and Warrant Officer training at the Combined Arms Center.

Some risk is associated with a tactical Army agent-based capability. Getting ahead of the science is the foremost of the concerns; it is vital to avoid letting the engineering process of developing an agent-based capability outpace the science. If engineering outpaces science, there can be the illusion of contextual oversimplification that results in users not trusting the capabilities that agent-based wargaming otherwise contributes. Another concern is whether validating the models and associated data availability is sufficient to ensure proper model validity. Finally, the study recommends the Army ruthlessly minimize the amount of time tactical users need to interact with and provide input to the produced tools and capabilities.

ABM is not an optimal or precision tool; rather, ABM is a robust capability that communicates a range of possibilities, including associated warning indicators with estimated possibilities of occurrence. The emphasis of the capability is first on understanding and modeling the situation within the larger context of human interactions and then working within the available Human Domain population.

Researching and developing an Army-centric ABM capability is a nontrivial task. The Army will need to devote significant person-hours to perform leading research and development, adequate verification and validation, subsequent model creation, and resource revisions. Similarly, a nontrivial amount of money, appropriated throughout the range of Basic Research–Operational System Development money, and people, serving in both stateside and training positions, will be required. However, little or no Army doctrine change is likely to be necessary.

1. Introduction

Operational art, the creative thinking used to design strategies, campaigns, and major operations and organize and employ military force, allows commanders to understand the challenges facing them and to conceptualize approaches for achieving the nation's strategic objectives. The underlying thought process helps commanders and their staffs to lessen the ambiguity and uncertainty of a complex operational environment, understand the military problem facing them, and visualize how best to effectively employ military capabilities to accomplish their mission (Joint Chiefs of Staff 2011, p. 1–5).

This report asks the question, Could the art of mission planning and campaign design, where critical and creative thinking are used to understand the fundamental nature of a complex military problem, benefit from new opportunities provided by mathematics and science? Might recent advancements in computational social science, agent-based modeling (ABM) and simulations, and complex adaptive systems offer Commanders and their planning staffs new opportunities to do the following:

- Rigorously explore and make sense of interactively complex operational environments.
- Unveil the nature of ill-structured military problems.
- Move beyond logical limitations of the linear, reductionist methods used in the intelligence preparation of the battlefield (IPB).

In other words, in an operational environment characterized by interactive complexity, emergence, and near-constant change, in institutions where there is no such person as a "subject matter expert" (SME) able to wrap their mind around hundreds of operational variables (i.e., political, military, economic, social, information, infrastructure, physical environment, and time [PMESII-PT]), subsystems, and their interrelationships, can the Science and Technology (S&T) community deliver an agent-based or game-theoretic capability that helps commanders and their planning staffs to more rigorously wargame and explore relevant "what if" scenarios before selecting friendly courses of actions? Could technology developers design an agent-based capability relevant to staffing and other "situational understanding" enablers resident within a brigade combat team (BCT)? Alternatively, would such a capability need to reside at a higher level of operations?

Thus, the central purpose of this report is to explore the relevance of agent-based models and research, and related game-theoretic concepts, to the improvement of tactical wargaming rigor (Sensenig 2015a, 2015b, 2015c).

1.1 Operational Problem

Future warfare will likely remain characterized by uncertainty. Politicians will send US forces to war while having varying depths of understanding of the specific complex factors contributing to violence, fear, and depravity. Commanders, their planning staffs, and intelligence analysts will encounter military problems that exist in 4 different knowledge states, simultaneously: known, knowable, complex, and chaotic.

1.2 Known

Behavior of a uniformed enemy is somewhat predictable because it is based on doctrine, movement rates, and the limitations of weapon systems and on the interaction of system components that are not individually purposeful. Observation of a single system component can lead to reasonable conclusions about the behavior of the larger system. This knowledge state is amenable to the present-day IPB.

1.3 Knowable

Before a conflict, US forces appreciate the need for a complete understanding of adversary behavior and the local population. Nevertheless, cause-and-effect can be discerned over time using wide area surveillance, pattern of life techniques, big data collection and mining, or simply by talking to the right people at the right time. There is general agreement among decision-makers from the White House to the BCT about the nature of the military problem, goals, and objectives.

1.4 Complex

Interactively complex military problems run the risk of oversimplification in Washington, DC and at higher levels of command. Behavior of various individuals, groups, and networks is not directly observable, not all interactions are understood, emergence creates unpredictable situations, and solutions to murky problems may have totally unexpected consequences. Cause-and-effect becomes coherent only in retrospect and does not necessarily repeat. Complex military problems make it difficult for tactical Commanders to link missions to strategic goals.

1.5 Chaotic

Chaos theory suggests that greater system complexity induces less predictable emergent behavior. There is no presumption of rational choice, of order, or of a unitary and stable threat. Some experts have described the chaotic knowledge state as the domain of the inconceivable—the black swan.

The impetus behind this study is more than theoretical. Summing up a consensus of lessons-learned literature over the past 15 years, "Military professionals describe the volatile mix of factors (e.g., mission, enemy, terrain, troops available, time, and civilian considerations [METT-TC]; area, structures, capabilities, organizations, people, and events [ASCOPE]; sewer, water, electricity, academic, trash – medical, safety and other [SWEAT-MSO]; and PMESII-PT) as being ambiguous, complex, uncertain, and ill-structured. When trouble appears, there is no consensus about what the fundamental problems are, how to solve them, what the desired 'end state' should be, and whether an 'end state' is achievable or not" (Perez 2011).

In a 2012 analysis titled "COIN [counterinsurgency operations] is Dead – Long Live Transformation," the authors described the difficulty of understanding the complexity of actors in Helmand Province, Afghanistan:

> Even after extensive British and coalition efforts to improve the collection, fusion, and assessment of a wide range of intelligence and information sources, the linkages between actors at the strategic and tactical level, between the Taliban, al Qaeda, local communities and national governments such as Pakistan have proven hard to identify, and their impact on local outcomes in Helmand have proven difficult to influence. Even in late 2011, the former International Security Assistance Force commander General Stanley McChrystal noted a frighteningly simplistic view of the country remained and was crippling the NATO war effort (Ford et al. 2012).

Closer to home, MG Michael Flynn's "Fixing Intel: A Blueprint for Making Intelligence Relevant in Afghanistan" (2010) asserted:

> Eight years into the war in Afghanistan, the US intelligence community is only marginally relevant to the overall strategy. Having focused the overwhelming majority of its collection efforts and analytical brainpower on insurgent groups, the vast intelligence apparatus is unable to answer fundamental questions about the environment in which US, and allied forces operate and the people they seek to persuade. Ignorant of local economics and landowners, hazy about who the powerbrokers are and how they might be influenced, incurious about the correlations between various development projects and the levels of cooperation among villagers, and disengaged from people in the best position to find answers – whether aid workers or Afghan soldiers – US intelligence officers and analysts can do little but shrug in response to high level decision-makers seeking the knowledge, analysis, and information they need to wage a successful counterinsurgency.

Finally, a RAND National Defense Research Institute analysis from 2014, "Modeling, Simulation, and Operations Analysis in Afghanistan and Iraq: Operational Vignettes, Lessons Learned, and a Survey of Selected Efforts", cites a relevant US Army Training and Doctrine Command (TRADOC) Analysis Center Irregular Warfare (IW) Working Group Report (Connable et al. 2014). In 2014, following 13 years of Army experience in Afghanistan and Iraq, researchers from the TRADOC Analysis Center examined methods, modeling, and analysis in support of IW. The study had 3 goals:

1) Determine the analytic community's, not just the intelligence community's, ability to support the commander's decisions during irregular warfare.
2) Identify gaps in Department of Defense IW analysis and analytics.
3) Recommend solutions to mitigate the gaps.

The working group's key findings are directly pertinent to this report: The group concluded that the highest risk gaps occur in protracted campaigns, in decision analytics associated with the civilian populations, understanding interactions between actors, in psychological operations, and in civil–military operations. The study identified 56 analytic capabilities used to support IW decisions, and identified 35 major capability gaps in IW decision analytics. Of those 35 gaps, 20 required social-science expertise.

This 2014 study told us something that most of us having years of experience in Iraq and Afghanistan knew all too well: The Army lacks decision-support tools designed to help commanders and planning staffs understand interactively complex situations involving hundreds of PMESII-PT subsystems and their impact on mission variables.

1.6 Why an Agent-Based Capability, and Why Now

Agent-based capabilities are integrated with emerging computational social sciences and practiced Army wargaming techniques to reveal emergent properties and behavior of militarily relevant individuals, groups, and networks in any operational environment marked by interactive complexity.

The behavior of individual parts results in interactive complexity. The greater the freedom of action of each individual part and the more linkages among the components, the greater is the system's interactive complexity (Department of the Army [DA] TRADOC 2008).

Agent-based capabilities begin with software agents, which represent battlefield entities that exhibit feelings and emotions (psychology), display behaviors (sociology), have goals and intentions, and either act or do nothing. The research and engineering challenge is to design and develop an agent-based capability adept at meeting the demands of a brigade planning staff. The authors recommend the brigade, or the BCT, because the brigade is the lowest level of command that can operate independently as part of a joint task force (JTF).

The BCT's unique capabilities—not found at battalion and below—allow strategic and operational military planners to employ the BCT in a variety of conditions, circumstances, and influences. The BCT is a modular organization that provides the land component or JTF commander with close-combat capabilities across the full spectrum of conflict. BCTs are the Army's tactical combat power-building blocks for maneuver and are the smallest combined arms units that can be committed independently. The challenge facing the S&T community is to design an agent-based capability of sufficient complexity and granularity, sufficient for surprising and useful results but not so complex that it becomes confusing, generates "noise in the analysis", or takes too much time, given time limitations that exist as a BCT staff conducts deliberate planning in preparation for war.

The recent developments of cheap computational power and software capable of representing agents with reactive and adaptive behavior provide engineers, scientists, and capability developers with a virtual laboratory. Legacy campaign simulations are a misfit of algorithmic, homogenous statistical models that cannot accurately represent interactively complex and diverse battlefield entities. Computational social science is now mature enough to revolutionize tactical Army-specific agent-based capabilities.

1.7 Study Overview

This report is composed of 5 sections: State of Wargaming, Agent-Based Modeling in Tactical Wargaming, Modeling Human–Computer Decision-Making, Existing Research and Applied Development of Agent-Based Modeling, and Plan for Research Development, Technology, and Training.

Section 2, State of Wargaming, begins with a summary of Army wargaming, followed by an introduction to the history of wargaming application. This section identifies analytical frameworks the Army uses to communicate strategic and operational situational understandings to tactical commanders and identifies challenges to current Army wargaming practices.

Section 3, Agent-Based Modeling in Tactical Wargaming, introduces the concept of ABM, especially with respect to the Human Domain. It explores the application of ABM to tactical wargaming, examining how it can improve the rigor of the current wargaming process.

Section 4, Modeling Human–Computer Decision-Making, begins with a survey of artificial intelligence and explores how ABM relates to broader artificial intelligence capabilities. This section discusses several decision-making frameworks from the perspective that decision-making is a traditional human-cognitive process and artificial intelligence is a capability that can assist the human. It then discusses agent-based design principles and patterns, in which each agent embodies their own decision-making capabilities.

Section 5, Existing Research and Applied Development of Agent-Based Modeling, reviews current state-of-the-art ABM capabilities, exploring tools that exhibit agent-based capabilities, identifying a framework for determining the maturity of such research, and reviewing how current agent-based research could assist the Army in creating a future tactical wargaming capability.

Section 6, Plan for Research, Development, Technology, and Training, presents the authors' recommendations, beginning with a holistic Army perspective, then addressing specific technologies and capabilities and identifying training and education recommendations, specific to the implementation of agent-based capabilities.

2. State of Wargaming

Wargaming is a process of thinking of and visualizing events that could occur during a possible course of action. Initially intended as an asymmetric battlefield planning capability, wargaming has matured into a formalized process over the past 200 years. In recent history, wargaming has become a standardized part of the Army military decision-making process (MDMP), helping staff to consider and evaluate actions and corresponding counteractions at strategic, operational, and tactical levels.

In this section, the report identifies and investigates what wargaming is, specifically, as the Army defines and applies it at the tactical level. The section begins with a review of the theoretical and conceptual notions of wargaming and connects them to the Army's wargaming practices. The study summarizes the evolution of Army wargaming, and other countries' application of wargaming, to provide the reader with context. Then, it reviews current analytical frameworks the Army uses to express operational requirements and situations. These frameworks illustrate the breadth of variables the Army considers during tactical analysis of courses of actions, or wargaming. Often, these frameworks are used to communicate inputs and outputs to and from the decision-making process. Finally, the report identifies challenges with current tactical Army wargaming.

2.1 Army Wargaming

The Army MDMP is an iterative planning process that integrates the activities of the commander, staff, subordinate headquarters, and other partners. An overview of the 7-step MDMP process is outlined in Fig. 1. Its objective is to allow these parties to understand the current situation and mission, develop and compare courses of action, decide on a course of action that would best accomplish the mission, and produce an operation plan or order (Headquarters [HQ] DA, FM 5-0 2010). According to doctrine, commanders use the full MDMP process if they have enough planning time and the staff to support an examination of 2 or more course of actions (COAs) and fully develop a synchronized plan or order (HQ–DA ATTP 5-0.1 2011). In a tactical context, developed COAs include both the most dangerous and most likely enemy COAs.

Key Inputs	Steps	Key Outputs
• Higher headquarters' plan or order or a new mission anticipated by the commander	Step 1: **Receipt of Mission**	• Commander's initial guidance • Initial allocation of time Warning order
• Higher headquarters' plan or order • Higher headquarters' knowledge and intelligence products • Knowledge products from other organizations • Design concept (if developed)	Step 2: **Mission Analysis**	• Problem statement • Mission statement • Initial commander's intent • Initial planning guidance • Initial CCIRs and EEFIs • Updated IPB and running estimates • Assumptions Warning order
• Mission statement • Initial commander's intent, planning, guidance, CCIRs EEFIs • Updated IPB and running estimates • Assumptions	Step 3: **Course of Action Development**	• COA statements and sketches • Revised planning guidance • Updated assumptions
• Updated running estimates • Revised planning guidance • COA statements and sketches • Updated assumptions	Step 4: **COA Analysis (War Game)**	• Refined COAs • Potential decision points • War-game results • Initial assessment measures • Updated assumptions
• Updated running estimates • Updated assumptions • Refined COAs • Evaluation criteria • War-game results	Step 5: **COA Comparison**	• Evaluated COAs • Recommended COAs • Updated running estimates • Updated assumptions
• Updated running estimates • Evaluated COAs • Recommended COA • Updated assumptions	Step 6: **COA Approval**	• Commander-selected COA and any modifications • Refined commander's intent, CCIRs, and EEFIs • Updated assumptions Warning order
• Commander-selected COA with any modifications • Refined commander's intent, CCIRs and EEFIs • Updated assumptions	Step 7: **Orders Production**	• Approved operation plan or order

Fig. 1 An illustration of the Army's MDMP identifies and associates key inputs and outputs with each step of the process (HQ–DA FM 5-0 2010, p. B-3; ADRP 5-0 2012).

Wargaming is the fourth step of MDMP and, as discussed earlier, understood as the systematic analysis of possible courses of action. A COA is a plan to accomplish a military objective, using friendly strengths and dispositions, known enemy assets, and possible resultant friendly and enemy courses of action within the context of an area of operations (HQ–DA ATTP 5-0.1 2011, p. 4–22; ADP 3-0 2011; ADRP 2-0 2012). Once stakeholders can visualize a system and its logic, they may gain insight into anticipating future behavior, identifying second and third order effects, accurately conceptualizing risk, and potentially influencing outcomes (ADRP 6-0 2014). However, wargaming does not guarantee selection of the best scenario; it is only an evaluation of identified COAs.

Wargaming tests, identifies, and adjusts identified COA deficiencies based on identification of unexpected events, tasks, requirements, or problems. During the wargame, staff transforms each COA into a detailed plan, while at the same time noting its strengths and weaknesses. Staff evaluates all forms of operations, including offensive, defensive, stability, and civil support. Within each COA, staff evaluates each critical event in terms of the action, reaction, and counteraction methods of interaction. The result is a refined set of actions, each with their respective synchronization matrixes. Completed decision-support templates and synchronization matrices portray both key decisions and potential actions, which are likely to arise during execution.

The wargaming of each COA allows staff to synchronize tactical tasks across the warfighting functions. For example, staff could maximize combat power while protecting friendly forces, anticipate operational events, determine conditions and resources for success, and identify the most flexible COA (HQ–DA FM 101-5 1997, p. 5–16). Figure 2 enumerates a nonexhaustive list of considerations illustrating the breadth of consideration involved in evaluating COAs.

Intelligence	• Intelligence, surveillance and reconnaissance • Knowledge gaps • Enemy course of action • Priority intelligence requirements • High-value targets	• Terrain and weather factors • Local environment and civil considerations • Counterintelligence • Intelligence support requests • Intelligence focus during phased operations	• Desired enemy perception of friendly forces
Protection	• Protection priorities • Priorities for survivability assets • Air and missile defense positioning • Terrain and weather factors • Intelligence focus and limitations for security	• Acceptable risk • Protected targets and areas • Vehicle and equipment safety or security constraints • Environmental considerations • Unexploded ordnance	• Operational security risk tolerance • Rules of engagement • Escalation of force and nonlethal
Movement and Maneuver	• Initial commander's intent • Course of action development guidance • Number of courses of action to consider or not consider • Critical events • Task organization • Task and purpose of subordinate units	• Forms of maneuver • Reserve composition, mission, priorities and control measures • Security and counter-reconnaissance • Friendly decision points • Branches and sequels	• Reconnaissance and surveillance integration • Military deception • Risk to friendly forces • Collateral damage or civilian casualties • Any condition that affects achievement of end state
Sustainment	• Sustainment priorities – manning, fueling, fixing, arming, moving the force and sustaining Soldiers and systems • Army health system support • Sustainment of internment and resettlement activities	• Construction and provision of facilities and installations • Detainee movement • Anticipated requirements of classes III, IV and V • Controlled supply rates	
Fires	• Synchronization and focus of fires with maneuver • Priority of fires • High priority targets • Special munitions • Target acquisition zones	• Observer plan • Task and purpose of fires • Suppression of enemy air defenses • Attack guidance • Branches and sequels	• No strike list • Restricted target list
Mission Command	• Friendly forces information requirement • Rules of engagement • Command post positioning • Commander's location • Initial themes and messages	• Succession of command • Liaison officer guidance • Planning and operational guidance timeline • Type of order and rehearsal • Communications guidance	• Civil affairs operations

Fig. 2 Table of Army warfighting functions and associated example considerations therewithal. Commanders issue guidance on items appropriate and applicable to the particular mission (HQ–DA FM 5-0 2010, p. D-1–D-4).

Participants involved in wargaming should remain objective and not allow external pressure to influence decisions, particularly while evaluating a COA they personally developed. Doctrine states that staff should record advantages and disadvantages as they become apparent and avoid premature conclusions and comparisons between COAs before wargaming is complete. Staff also continually assesses the feasibility, acceptability, and suitability of each COA, where feasibility is the actual practicality of executing the COA, suitability is the likelihood that the situation will result in the desired effect, and acceptability is the evaluation of whether the results are worth the cost.

2.1.1 Personnel and Roles

Army doctrine identifies a number of staff members who have roles to play during wargaming. Each of the warfighting functions has assigned staffs who provide relevant input (HQ–DA FMI 5-0.1 2008; FM 6-0 2016, p. 9–15). Identified staff include the Executive Officer, Assistant Chief of Staff, G-1 through G-9 (as appropriate, S-1 through S-9), Chief of Fires, Chief of Protection, Surgeon, Red

Team Officer, Staff Judge Advocate, Operations Research and Systems Analysis (ORSA) Officer, and Safety Officer. However, many of these defined positions do not exist as wargaming is used at increasingly tactical levels (e.g., division, brigade, and battalion units). As such, the breadth of participation, analysis, and contribution expected within doctrine is not realized.

The following are summarized descriptions of specific roles, which Army doctrine identifies and highlights:

- The Executive Officer (XO) coordinates actions of staff during the wargame, ensuring that staff stays on schedule. In time-constrained situations, the XO ensures the most decisive operation is wargamed (HQ–DA ATTP 5-0.1 2011, p. 4–24).

- The Assistant Chief of Staff and G-2 (S-2, intelligence) are responsible for the "intelligence" warfighting function. They role-play the enemy commander and capture the results of enemy actions and evaluate strengths and weaknesses of friendly and enemy units. They try to win each wargame for the enemy. Enemy decision points, enemy reactions to friendly actions, and projections of enemy losses are products of this effort. Recommended intelligence requirements and a refined event template with decision points are produced.

- The Assistant Chief of Staff, G-3 (S-3, operations), and G-5 (S-5, plans) are responsible for the "movement and maneuver" warfighting function and role-play the friendly maneuver commander. They execute friendly maneuvers as identified in the course-of-action sketch and the statement provided as input to the wargame. They also assess warfighting requirements, develop plans and orders, and identify possible branches; they also coordinate and synchronize warfighting functions. A decision-support template and matrix, annotated with action rationale, are products of this effort.

- The Chief of Fires is responsible for the "fires" warfighting function and develops metrics measuring effectiveness for fire support and evaluation. Named and targeted areas of interest are identified, along with a proposed high-priority list, target selection standards, and attack guidance.

- The Chief of Protection is responsible for the "protection" warfighting function, which develops a method of protection for each wargame. This role develops risk control measures and identifies critical and defended assets. Products include synchronizing recovery coordination, air and missile defense, and area operational security (HQ–DA ATTP 5-0.1 2011, p. 4–24, 4–25).

- The Assistant Chief of Staff, G-1 (S-1, personnel), G-4 (S-4, logistics), and G-8 (financial management) are responsible for the "sustainment" warfighting function. The G-1 identifies potential shortfalls in maintaining staffing. The G-4 assesses the status of logistics and movement functions. If the G-4 identifies shortfalls, they also recommend actions to minimize the effects. The G-8 assesses partner relationships, special funding situations, and procurement process to identify resource deficiencies.
- The Assistant Chief of Staff, G-6 (S-6, signal), G-7 (S-7, inform and influence activities), G-9 (S-9, civil affairs operations), Red Team Officer, Staff Judge Advocate, ORSA Officer, and Safety Officer are responsible for the "mission command" warfighting function. The G-6 assesses and recommends actions to minimize any negative effects of the electromagnetic spectrum, and evaluates network and information operations and protection. The G-7 assesses how actions will affect information operations, along with other consequences of interacting with the population. The G-9 considers how tactical and sustainment operations may affect public order and safety, disaster relief, evacuation, emergency services, and the protection of cultural sites. The Red Team Officer provides the commander and G-2 with the independent capacity to explore alternatives from the perspective of adversaries, partners, or others. The Staff Judge Advocate advises on matters pertaining to law, policy, regulation, good order, and discipline. The ORSA Officer provides quantitative support to planning, a quality control capability, and measures the effectiveness of operations. The Safety Officer develops a risk management strategy to help minimize accidents (HQ–DA ATTP 5-0.1 2011, p. 4–25, 4–26).

2.1.2 Wargaming Process and Tools

The Army wargaming process is composed of 8 steps, which includes gathering tools, listing all friendly forces, listing known assumptions, listing known critical events and decision points, selecting the wargaming method, selecting a recording tool, and finally, wargaming the course of action. Figure 3 and the following text describes each of these steps in more detail.

Key Inputs	Process	Key Outputs
• Updated intelligence preparation of the battlefield products • Updated running estimates • Updated commander's planning guidance • Course of action statements and sketches • Updated assumptions	• Gather the tools • List all friendly forces • List assumptions • List known critical events and decision points • Select the wargaming method • Select a technique to record and display results • Wargame the operation and assess the results • (optional) Conduct a war-game briefing	• Refined courses of action • Decision support templates and matrixes • Synchronization matrixes • Potential branches and sequels • Updated running estimates • Updated assumptions

Fig. 3 An expanded illustration of the MDMP wargaming step, with identified inputs, outputs, and the process involved (HQ–DA FM 5-0, 2010, p. B-21)

The first step is for staff to gather tools necessary for the wargame (HQ–DA STP 34-350F-SM-TG 2006; FM 5-0 2010, p. B-25; ATP 2-01.3 2015). The XO directs staff to gather the necessary tools, materials, and data. Tools generally include running estimates, event templates, and a means to display enemy and friendly units, and other organizational tools. Resources traditionally include maps, sand tables, computer simulations, and other visual and interactive tools. Once gathered, staff places the individual course of action on a map, displayed within the area of operations.

The second step is to identify and display all units that could be committed to the operation. Additionally, staff should include assets from all involved parties, paying attention to logistical constraints.

The third step is for the commander and staff to review assumptions and ensure they are still valid and necessary.

In the fourth step, staff list all known critical events and decision points. Critical events are those that would directly influence mission success or would cause the commander to make a significant decision. Alternatively, this step includes actions requiring study. Reactions from civilians, whose actions could affect operations or require allocation for secondary population stability missions, are included. A decision point is a point in space and time when the commander must make a decision about a specific course of action. Decisions may be associated with friendly forces or with the status of operations, or they may result from a Commander's Critical Information Requirements request. However, decision points do not specify what the decision will be.

The fifth step is to select a wargaming method that helps staff consider both the area of interest and the participants who can affect the outcome (HQ–DA FM 5-0 2010, p. B-26). Three common methods exist: 1) belt, 2) avenue-in-depth, and 3) box, each of which may describe either a spatial area of operations or a lines-of-effort, event-based timeline. Figure 4 illustrates these methods.

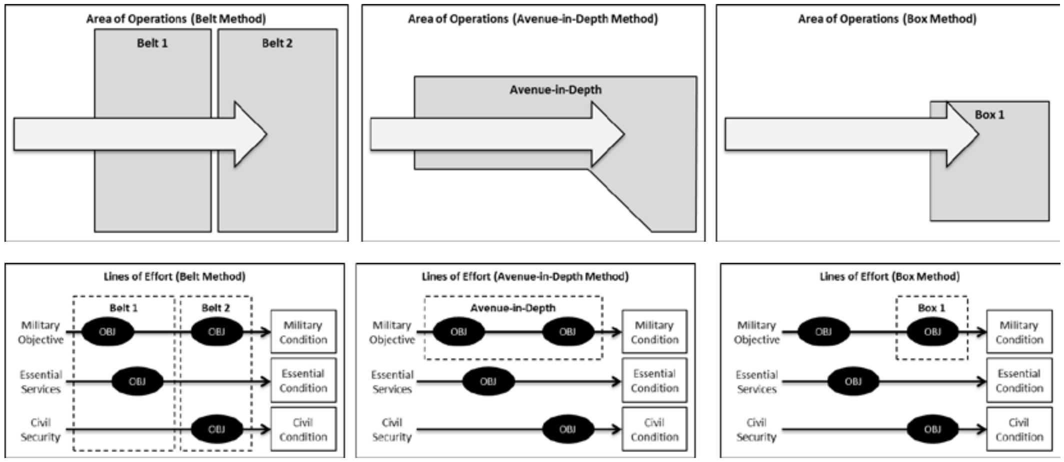

Fig. 4 Visual representations of each wargaming method are as follows: belt, avenue-in-depth, and box. The upper figures illustrate how they are applied in spatial areas of operations whereas the lower figures illustrate how they are applied to distinct lines of effort (illustrations adapted from illustrations in FM 5-0 [2010 p. B-26 – B-29] and FM 101-5 [1997 p. 5-18 – 5-21]).

The belt method works well for operations crossing terrain, dividing the area of operations into a series of parallel vertical strips. For example, this method is especially useful when there is a progression of sequential spatial steps, such as incremental navigation over terrain, or when there is a stratified deployment of enemy units. Alternatively, staff may use lines of effort in place of a spatial layout; in this case, each belt segment may include more than one critical objective or event, with each critical event derived from distinct lines of effort.

The avenue-in-depth method works well for decisive action, such as an offensive action. While this technique may use a spatial area of operations, it may alternatively illustrate specific lines of effort according to objectives, events, and interrelated relationships.

The box method is the contextually isolated means of analysis. Detailed analysis of a specific area works best during time-constrained situations or planning operations in noncontiguous areas of operation. In this technique, staff purposefully isolate spatial areas and focus on the critical events within their bounds.

The sixth step is to select a technique to record and display results (HQ–DA FM 5-0 2010, p. B-29). Results provide a record from which to build task organizations, synchronized activities, decision-support templates, event templates, plans and orders, and COA comparisons. Records can take the form of synchronization matrices or sketch notes. Synchronization matrices coordinate a course of action across time, space, objectives, and decision points in terms of each warfighting function. Comparatively, sketch notes identify pertinent information concerning specific spatial locations. If lines of effort are used, sketch notes identify a specific task or purpose. Sketch notes have a designated sequence number and identify information in terms of specific events, actions and reactions, and decision points rather than by each warfighting function. Figures 5 and 6 outline a template synchronization matrix and sketch notes, respectively.

	Time	T – 24 hours	T hour	T + 24 hours
	Enemy Action			
	Civilian Action			
	Decision Point			
Warfighting Functions	Intelligence			
Warfighting Functions	Protection			
Warfighting Functions	Movement and Maneuver			
Warfighting Functions	1st Infantry Battalion			
Warfighting Functions	2nd Infantry Battalion			
Warfighting Functions	3rd Infantry Battalion			
Warfighting Functions	Artillery Battalion			
Warfighting Functions	Sustainment			
Warfighting Functions	Fires			
Warfighting Functions	Mission Command			
Warfighting Functions	Electronic Warfare			
Warfighting Functions	Civil Affairs			
Warfighting Functions	Interagency			

Fig. 5 A template of a synchronization matrix; the second and third rows identify most likely enemy and civilian actions. Rows annotated as "Warfighting Functions" focus on specific tactical warfighting functions, with additional rows, as appropriate, added for subordinate commands (illustration adapted from FM 5-0 [2010, p. B-29]).

Critical Event	
Sequence Number	
Action	
Reaction	
Counter Action	
Assets	
Time	
Decision Point	
CCIR	
Control Measures	
Remarks	

Fig. 6 A template of a sketch note that identifies critical attributes of operations associated with decision points. Locations are marked on the map, and wargaming participants identify expected actions, reactions, and counteractions pertaining to each sketch note. (Illustration adapted from FM 5-0 [2010, p. B-31] and ATTP 5-0.1 [2006, p. 4-32]).

During the seventh step, staff wargame each course of action independently (FM 5-0 2010, p. B-30). They assess its individual results, strengths, and weaknesses.

Staffs then consider the range of options for each action, reaction, and counteraction; this occurs for all participants, including the civilian population. They identify necessary tasks and required assets, including tasks for one-echelon lower and using assets up to 2 echelons lower. The wargame tests the effects of action for both intended and unintended consequences. Participants consider all possible actors, such as friendly forces; enemy forces, including forces outside the area of operations; civilians; and media. Ideally, staff involved in the wargame analysis should have been originally involved in the development of the analyzed courses of actions (ATTP 5-0.1 2006, p. 4–33).

The eighth step is an optional step, consisting of briefing results to all stakeholders (FM 5-0 2010, p. B-33). The presentation acts as a quality control function and ensures proper communication and analysis. Content included within the briefing includes orders and the commander's intent, an updated IPB, assumptions, and the analysis technique used. Presentation includes critical events, possible actor actions and reactions, impact on the civilian population, possible media perception, strengths, weaknesses, and results. If identified during the wargame, the presentation may also include modifications to courses of actions. Figure 7 illustrates the inputs, considerations, and outputs of the wargaming process.

Identify	Analyze	Develop
• Key or decisive terrain • Retained vs. delegated tasks • CBRN plans and response • Most dangerous enemy COA • Most likely COA • Most dangerous civilian reaction • Critical events • Commander and command locations • Requirements for warfighting functions • Consequences of actions on civilians • Confirmation of areas of interest, decision points, and intelligence requests • Strengths and weaknesses of each COA • Control hazard risk • Interagency, host-nation and NGO involvement	• Civilian reactions • Media reaction • Impact on civil security and control • Impact on essential services	• Decision points • Synchronization matrix • Minimum essential stability tasks • Reconnaissance and surveillance plan • Informational themes and messages • Fires, protection and sustainment plans

Fig. 7 Illustration adapted representation of Table 9-5, Effective Wargaming Results (FM 6-0 2012, p. 9–35)

Each illustrated wargaming analysis produces an increased understanding of the complex necessities of the battlefield, such as requirements for deception and surprise, timing for concentrating and beginning attacks, identifying and coordinating movement timelines, and estimating durations of operations. Additional elements include projections of casualty rates, an identification of the minimal essential tasks, allocation, and prioritization of assets to appropriate sub-commanders, and possible resulting media coverage.

2.2 Conceptual Notion of Wargaming

As described earlier, wargaming is an interactive process of identifying, thinking about, and visualizing plausible events that could occur during a given course of action. Wargaming considers, evaluates, and projects involved actors, resources, environments, and their combined interactions. Some games and analyses simulate a similar type of holistic interaction, such as free-form games and game-theoretic analysis. However, in each of these examples, results of interactions are nondeterministic. As such, the outcome is not entirely predictable. However, one can characterize the nature of the output produced by these interactions. For example, one of the premises of wargaming is that if one makes specific assumptions, one gains decision-making insight that helps delimit the set of possible outcomes and their likelihoods of occurring, provided assumptions are and remain valid.

Several types of games exhibit properties applicable to wargaming. Two examples are so-called rigid and free-form games (Kretchik 1991, p. 5). Rigid games, such as chess or poker, identify specific rules before the game starts, and because a finite number of choices and moves exist, an optimum solution can be determined. For example, in chess, only one piece can move at a time. The benefit of such a game is that one can probabilistically identify the possibility of future actions.

Free-form games loosely define rules and participants are interactive. Consensus between participants often forms and frequently determines the game's result. The game of tag is an example where participants adjust the rules of the game according to environmental conditions. Compared to rigid games, free-form games better model realistic situations by embodying the flexibility of how actors interpret situations, interact with each other, select personal and group strategies, and make decisions. Because of the dynamic nature of interactions, emergent outcomes often result.

Game theoretic analysis is a branch of mathematics suited to the analysis of social situations and interactions. It is a technique modeling actor interaction, each with interrelated goals and, as such, it is useful for wargaming. Interaction manifests through the dynamics of friendly actions, enemy reactions, and friendly counteractions. The traditional game theoretic assumption is that each player selects an optimal strategy, without knowing the other player's strategies, and tries to obtain the best possible outcome. Game theoretic approaches make 3 assumptions: a rational actor, rational control, and strategies.

A rational actor considers its own interests and pursues a strategy to achieve a set of goals. The rational actor works against moves by opponents that prevent it from accomplishing its goals. Alternatively, an irrational actor exhibits properties such as not knowing what it wants, failing to define goals, and not seeking attainment of objectives.

Rational control assumes consistent rules and principles guide actors. Both rigid and free-form games are examples of such control. Both are consistent, in terms of their definitions, but express different phenomena.

The third assumption of game theoretic approaches is that actors will use strategies. Two ways of evaluating strategies exist: the first considers the spectrum of possibilities that any actor may take, and the second uses a selected strategy. If an actor is using a selected strategy, that strategy may create indicators that can cue opposing actors to the possibility of the decision. During wargaming, participants evaluate whether actors are able to execute a given strategy and whether a given actor has already made a decision. Wargaming participants evaluate these decisions by making intelligence requests for symptoms, identifying named areas of interest, and identifying the appropriate decision points (ATTP 5-0.1 2006, p. 4–24).

Another type of game combines rigid and free-form games; these are serious games. Serious games are an explicit and carefully thought-out educational learning experience (Abt 1968; Shaffer et al. 2005). This does not limit the enjoyment of serious games, but that is not their primary objective. The difference between casual and serious games are that the latter have a specific learning objective, engage participants with interactive media, and have some form of gaming aspect. Early forms of serious games used behavioral models, but recent games have sought to incorporate experiential, situated, and social–cultural models. Serious games are useful when there is some nominal amount of uncertainty or ambiguity. However, the utility of serious games is minimized if a high degree of uncertainty exits (Protopsaltis 2011).

Multiple models of learning are included during gaming, including constructive and experiential learning. Constructive learning enables participants to contrast mental models to understand the presented situation. Participants reinforce learning by explaining insights. In contrast, experiential learning is the result of action. The participant is immersed within a situation or task and actively works to resolve the situations. Different models for learning exist but many often follow a similar process: model of a virtual event occurs, participants interpret, reflect upon, and learn from the situation, and finally take action.

Regardless of the type of game, learning assessment remains difficult because of the open-ended nature of these types of activities. For example, skills used within the activity may include the ability to innovate, collaborate, think critically, produce a resulting product, and perform system thinking (Shaffer et al. 2005). However, the means to collect information on each individual skill is limited. Thus, some researchers have concluded that an evaluation of the process used may provide a better means of measuring value than the grading of factual results.

In wargaming, participants follow a rigid game, but there is a variety of actors, environments, decisions, and interactions, so free-form results can still emerge. Army doctrine ensures staff uses a consistent process to produce output and specifies outputs expected from wargaming. The first expectation is to list advantages and disadvantages as they become apparent during wargaming analysis. The second expectation is for all wargaming participants to remain unbiased and avoid influences by other members. The third expectation is for participants to evaluate the feasibility of each individual course of action and determine whether it meets mission objectives and requirements. The fourth expectation is for participants to avoid comparing any course of action with another during the wargaming stage; course-of-action comparison is a process that takes place after the wargaming process is complete, after which the commander makes a decision in a subsequent MDMP step. Finally, the last expectation is to avoid premature conclusions; instead, staff should present facts for each course of action independently (FM 6-0 2016, p. 9–36).

Several theoretical perspectives and resulting methodologies guide wargaming analyses, each dependent on the individual participants' perspective of risk (Wang and Ruhe 2007). One approach analyzes a set of possible courses of action, evaluates the enemy's capabilities, and chooses the least risky option to friendly objectives. Another is similar to the first but analyzes possible courses of actions from an assumed enemy perspective. As such, the second approach embodies an optimistic approach because participants attempt to model enemy intentions and choices before action has actually begun. In both perspectives, participants assume rational actors. However, the underlying assumptions of each participant influence the wargame, actor choices, and analysis. Selection of one approach over the other is a function of how much risk each participant estimates the commander will accept.

From the standpoint of theoretical methodology, the first perspective models the game theoretic maximin selection methodology (Haywood 1951). Participants express analyses as an evaluation of the detected enemy capabilities. Wargaming participants assume rational actors in both friendly and enemy forces, which imply that both forces will establish objectives, pursue distinct courses of action, and attempt to block each other's opposing actions. Moreover, once analyses are complete, the participant assumes the commander would like to select a course of action that has more advantages than disadvantages.

Army doctrine specifies several wargaming products, one of which is a comparison matrix of possible friendly courses of action versus enemy COAs. In this matrix, each COA comparison has an associated predicted outcome, such as the likely success of the friendly COA. Maximin theory states that a temporary set of worst-possible outcomes for each friendly COA is created, from which the best-possible outcome is selected as the appropriate COA. The selected COA is ideally the most robust selection but is not optimal, since the methodology assumes that friendly forces will act first, which is a theoretical disadvantage. An example of the maximin selection process in shown in Fig 8.

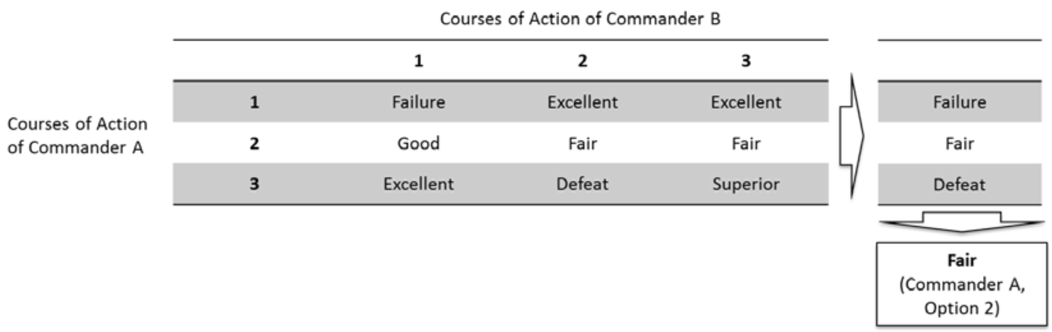

Fig. 8 An illustration of the decision-making process using the maximin process. In this example, outcomes of each course of action combination are identified. The selection process identifies the worst-case outcomes for each COA; in this case, from the perspective of Commander A. From those outcomes, Commander A selects the best-case scenario (Kretchik 1991, p. 8).

Comparatively, the second perspective models the game theoretic minimax selection methodology. Participants analyze the situation from the enemy's perspective and try to identify the enemy's intentions. As in the first perspective, participants assume rational actors. However, in the second, participants develop COAs to take advantage of suspected enemy-first moves, and predict future actions.

Similar to the first technique, a comparison matrix is produced comparing friendly and enemy COAs with their estimated results. However, this second approach is not without its risks—confusing indicators result from deception, random enemy activity, and the fog of war. When conflicting indicators appear, the recommended process is to weigh each indicator, placing more weight on indicators that are indicative of intent. Minimax theory states that a temporary set of best-possible outcomes for each friendly COA is created, from which the worst possible outcome is selected as the appropriate COA. Using this methodology allows the participant to select a theoretically more optimal COA than the first technique because it assumes enemy intent is discernable prior to action. An example of this alternative minimax selection process is shown in Fig. 9.

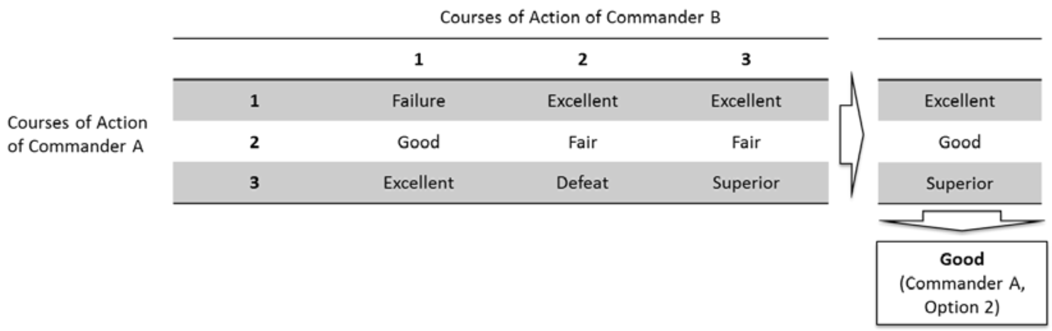

Fig. 9 An illustration of the decision-making process using the minimax process. In this example, outcomes of each course of action combination are identified. The selection process identifies the best-case outcomes for each COA; in this case, from the perspective of Commander A. From those outcomes, Commander A selects the worst-case scenario.

2.3 History of Army Wargaming

Formal wargaming in the United States began in the late 1800s with a book called *The American Kriegsspiel: A Game for Practicing the Art of War upon a Topographical Map*, published by MAJ WR Livermore (1882) in the US Army Corps of Engineers.* This book was an American application of German wargaming techniques, originally based on the writing of von Tschischwits and translated to English by CPT Baring (Young 1956, p. 14).

American Kriegsspiel suggested playing the game using 3 maps, each in different rooms, to segregate each team's information and knowledge. Two of the rooms contained personnel representing friendly and enemy forces, respectively; each team knew its own state but did not have a comprehensive view of the entire battlefield. The third room recorded the entire game (i.e., ground truth) on a board called the Firing Board, which an umpire used. The umpire used lookup tables and charts detailing the rates of movement under different conditions, calculations of losses, and effects of fire. The game modeled the effects of a variety details, such as fire, fatigue, level of training, morale, and terrain variations, on actions and interactions during the game.

After publishing his book, MAJ Livermore proposed the game to the Army. However, the Army's Chief of Staff at the time, GEN Sherman, did not approve.

* Another individual, LT Totten, also produced a similar type of game. However, LT Totten published his version after MAJ Livermore's (Young 1956, p. 16). A major difference between the 2 games was LT Totten's version specified 2 levels of difficulty, beginner and advanced.

He justified his decision by stating that the wargame "depicted men as if they were blocks of wood rather than human beings seized by fear and sustained by leadership" (Caffrey 2000). This was because the game's rules did not account for psychological breaking points. For example, the game depicted attrition as units fighting to the last man. However, after several years of effort, in 1899 the Army established a war college and included wargaming in the curriculum.

Over time, the Army improved on the original game, changing from wooden blocks to transparent overlays, which documented and recorded moves for subsequent analysis, among other changes. The Army also created a standardized operations order format, given to the umpires, to adjudicate actions.

Creating estimates of the situation became Army doctrine in 1910 and first published in FM 101-5 in 1932 (Fig. 10). This publication documented the origins of the military decision-making process, which originally consisted of 5 major steps: Mission, Opposing Forces, Enemy Situation, Own Situation, and Decision. Elements of wargaming were included in this process and identified as "Analysis of Plans".

1. Mission
2. Opposing Forces
    1. Enemy Forces
    2. Own Forces
    3. Relative Combat Strength
3. Enemy Situation
    1. Plans Open to Enemy
    2. Analysis of Enemy's Plans
    3. Enemy's Probably Intentions
4. Own Situation
    1. Plans open to you
    2. Analysis of Plans
5. Decision

Fig. 10 The original specification of the MDMP, first documented in FM 101-5, 1932 (figure adapted from Table 1: Format of the Estimate [Michel 1990, p. 5]).

Little else changed until the pre-World War II era. Wargames were primarily used for instruction and the training of field maneuvers. However, over time free-form wargames (also known as *Free Kriegsspiel*) increased in Army importance and use.

In 1927, von Neumann suggested the theory and potential of a rigid type of wargame (i.e., game theoretic analysis). In 1944, von Neumann and Morganstern published an account of game theory in their book *Theory of Games and Economic Behavior* (Young 1956, p. 23). They described situational consequences as the result of combining actions of friendly decision-makers with those of the opponent.

In the 1940s, the Army began to improve the rigor of wargaming. Historians have lauded the Army's Chief of Staff, GEN Marshall, for the improvement. He liked wargames from the time he was a junior officer and, with the likelihood of war growing, he directed that wargames be executed as field exercises.

During World War II, both the British and Germans used an intentions-based technique for their wargaming. When America entered the war, it was using a similar technique; as such, the United States began using British intelligence for strategic and tactical information. However, after a short time the Army discontinued its practice of estimating enemy intentions because they learned the danger of underestimating the enemy (Lewis 2004). After the war, the War Department agreed with the decision and concluded that estimating enemy intentions had not substantially improved intelligence results.

Once World War II ended, much of the Army's wargaming effort ceased until the Army realized it might have to fight the Soviet Union. This renewed realization of the value of wargaming came from debriefing German officers, as American personnel learned the value of the Germans' wargaming practices. One of the lessons learned included identifying enemy intentions, a practice the Army had originally discarded because of the risks it encouraged. However, the Army once again adopted the procedure of estimating and including enemy intent into its wargaming.

In 1951, a RAND study by COL Haywood identified the applicability of game theory to military situations. His proposal that decisions should be based on an estimate of enemy intentions rather than on their capabilities eventually became integrated into modern Army wargaming doctrine.

Haywood also suggested sequential action and counteraction matrices be developed during wargaming. These matrixes are nearly identical to 2-person, zero-sum games identified in game theory. As such, those games facilitated use of both the maximin and the minimax decision-making methodologies. However, the zero-sum game introduced an assumption that both friendly and enemy forces were rational and employed identical concepts of military worth. It also assumed decisions, based on estimates of enemy intentions, would result in outcomes at least as favorable as those identified by the alternative assessment methodology using enemy capabilities.

During the 1960s, helicopter enthusiasts used wargaming to develop the concept of the air-mobile division (Caffrey 2000). This was similar to how Germany used wargaming to develop *Blitzkrieg* tactics, techniques, and procedures. Defense Secretary McNamara directed the Army to follow through with the concept.

However, in this case, once the Army deployed its first helicopter division, it quickly found combat was different from wargaming.

Decision-makers also discovered wargaming results had not anticipated the political consequences of decisions. As a result, in 1964 the Advanced Research Projects Agency funded efforts to produce a wargame that depicted all political, psychological, and economic ramifications of an insurgency. Despite the availability of these improvements, the defense planning community continued to use traditional attrition-based wargames.

In 1974, the Army became the first service to buy a commercial wargame, the tactical ground-combat simulation "Fire Fight" (Caffrey 2000; Dunnigan 2005). In 1980, the Army opened the National Training Center (NTC), which employs an instrumented range, technology similar to laser tag, and a credible aggressor force to produce a realistic ground-combat environment. Wargaming became more popular once each maneuver base established wargaming centers. Commanders realized it took less time to set up wargames than to set up other forms of training.

During the first Gulf War, NTC used wargaming exercises to prepare Soldiers for deployment. Individual Army units began to wargame their own responsibilities with respect to attack plans. In one instance, an Army unit used a commercial wargame for training. However, similar to other historical applications, wargames still had the risk of misleading commanders. For example, the predicted number of causalities during the first Gulf War was higher than was actually realized. This caused commanders to configure transport aircraft for medical airlift. However, once the expectation was realized as invalid, commanders reconfigured transport aircraft to transport fuel, which turned out to be the actual need.

2.4 Historical Evolution of Wargaming

The following describes the historical context of wargaming, illustrating several of the similarities and differences between current and historical practices. It also identifies examples of how militaries have used wargaming throughout history.

Informal wargaming, or the consideration of actions, reactions, and counteractions, has likely existed since the beginning of human history. Historical first-generation games such as chess and Go are abstract representations of conflict and war, likely developed years ago in the Far East to help players consider, visualize, and practice decision-making and learn consequences of courses of action. In combat, it was historically the commander's responsibility to visualize situational contexts and make the appropriate decisions. Anecdotes, such as Napoleon's use of toy soldiers to visualize battle sequences, illustrate this level of responsibility and forward planning.

Historians credit the Prussian Baron von Reisswitz with the development of the second-generation wargame. In 1811, he constructed a table-sized model of terrain and used blocks to represent units; this was the predecessor to the Army sand table. Players would give orders to an umpire, who in turn updated the terrain table, resolved combat, and informed players of the knowledge they had of the battlefield. Umpires derived casualties by using lookup tables, the roll of a die, and contextual attributes like range and terrain.

The Prussians developed the idea of training professional staff officers, and wargames evolved to help them visualize battles from start to finish. Reisswitz's game was adapted to topological maps in 1824, and thereafter wargaming became standard in Prussian Army practice. As early as 1828, then LT von Moltke advocated use of wargames. Nine years later, GEN von Moltke became Chief of Staff of the Prussian Army and ordered an increase in the use of wargaming. He also used wargaming performance as an evaluative criterion for acceptance into the War College, where wargaming was a regular part of the curriculum.

Periodically, GEN von Moltke would take the entire War College student body out to a possible invasion corridor. He would describe the most likely first clash to all the students, then turn to the most junior student and ask for his plan of battle. Next, he asked the second most junior and so forth until all students provided their plans. After coming to a consensus for a battle plan, GEN von Moltke designated the next senior ranking general after him to command the invading forces and the next ranking general after the first to command the Prussian forces. He split the students into 2 equal teams and assigned one team as invading commanders and the other as Prussian commanders. Once the game had been completed, GEN von Moltke would direct the local garrison commander to march several hundred troops to gather marching times and other details of the plan. Once complete, the plan became the actual Prussian defense plan for an invasion along the exercised corridor.

In the 1860s, the Prussians began using wargaming as a decision-making aid. Over time, GEN von Moltke won a series of wars against opponents who sometimes had larger forces, and other militaries began to adopt the Prussian wargaming technique. However, Prussia/Germany continued to adapt its wargaming techniques.

For example, CPT Naumann published rules for identifying breaking points in 1877. These rules identified criteria for determining at what casualty levels units would cease functioning. This was an improvement over the existing process, which used attrition tables to simulate interactions. Interestingly, these rules were missing from the early American wargaming adaptations in the late 19th century and were one of the primary reasons GEN Sherman rejected the technique.

The second adaptation was *Free Kriegsspiel*, a controversial modification developed in the mid-1870s. Proponents of *Free Kriegsspiel* advocated a radically different type of wargame, which allowed experienced participants to substitute their personal military judgment for many of the time-consuming adjudication rules. Initially, the *Free Kriegsspiel* technique worked well, but over time, participants could not adjudicate results accurately due to a lack of actual combat experience.

Additionally, using a *Free Kriegsspiel* methodology, ranking participants began to override umpire-adjudicated results based on their professional judgment. The immediate result of this modified wargame was a more popular game. Participants could complete wargames faster and they would play wargames more often and gain confidence in their results. However, in practice this methodology led to negligent analysis and overconfidence, which contributed to significant military defeats.

2.5 Historical Applications of Tactical Wargaming

The British military experimented with wargaming briefly around the turn of the 19th century. The British Parliament listed wargaming as a hobby, and a civilian naval wargame was the reason for the development of the annual reference book, cataloging the world's military warships, *Jane's Fighting Ships*. However, the popularity of wargaming subsided as the British discovered it could not address the psychological or political dimensions of the Boer War.

The Russians also began adopting wargaming practices but chose to use the *Free Kriegsspiel* methodology. For example, one wargame during 1914 demonstrated a successful means of advance against German forces. However, at a critical point where terrain made communication difficult, the commanding Russian generals overrode the negative, adjudicated results and said the strategy would be successful. Four months later, the same scenario and plan as that within the wargame played out, and the Russians made the same progress as suggested by the wargame. However, when the Russians encountered the same difficult terrain simulated in the wargame, German forces prevailed against the Russians.

Prior to World War II, Germany continued to improve their wargaming technique. Since wargaming could model attrition but neglected other aspects, such as political effects, the German government began running strategic-level wargames to compensate for the political deficiency. Limited to their post-World War I situation, Germany decided it could wargame with military forces it did not possess. Based on historical lessons, the Germans were able to derive new theories and develop unique military doctrine. This new doctrine was wargamed to see whether it might work; some of it did and was eventually termed mobile-operations or *Blitzkrieg*. Interestingly, when Adolf Hitler came to power, he halted strategic-level wargames (Caffrey 2000).

Throughout World War II, the United States, Russia, Germany, and Japan each wargamed possible battlefield situations, each with varying degrees of tactical success. The Navy used wargaming to develop the carrier attack-group formation. The Marines used and refined its wargaming techniques to the point where they could accurately predict battle outcomes and logistical needs; it became so accurate that it eventually detected the change in Japanese strategy, which emphasized loss of life. Similarly, Russian GEN Zhukov wargamed Germany's battlefield tactics accurately. Japan wargamed the emerging tactical World War II situation to decide whether to enter the war; however, the wargame did not include political considerations. Japan later ran wargames indicating it would lose the war, and that prompted Japanese leaders to adopt a new strategy.

Despite resistance to strategic wargaming, Germany continued to use tactical wargaming extensively throughout World War II. In early 1944, the Germans conducted a wargame of a possible Allied invasion of France that focused on logistical preparation. When reconnaissance spotted preparations across the Channel from Normandy, the Germans conducted a wargame of an Allied landing at Normandy. While the German opinion was that an Allied invasion was a feint, the Germans concluded that if the feint were successful, the Allies might make that their primary attack. Initial reinforcements, resulting from this wargaming conclusion, made the D-Day invasion on Omaha Beach one of the most difficult battles of the Normandy invasion. Ironically, assisting the Allies' invasion, another German wargame was taking place when the D-Day invasion began. It was evaluating the possibility of an Allied invasion of Normandy, with all their reinforcements in place. However, because the wargame took place during the actual invasion, it had the effect of keeping key German commanders from participating during the initial stages of the Normandy invasion.

Another tactically applied German wargame was during the Battle of the Ardennes, in the fall of 1944; the Fifth Panzer Army conducted a wargame of an American attack on their position. Coincidently, during the wargame, the Americans attacked. However, Field Marshall Model did not stop the wargame; instead, movements from the field stimulated actions within the wargame. The Germans used the opportunity to wargame each order before actually executing it (Young 1956, p. 21).

After World War II, countries continued to develop their specific versions of wargaming practices. For example, American wargaming changed from a commander's task to a staff function informing the commander and helped institutionalize COA analysis. This contrasted with Britain's and Germany's approach, where staff was responsible for developing COAs but the commander was exclusively responsible for their analysis.

Both pros and cons arose from these changes. The American version could cause the decision-making process to take more time, due to additional analysis, but the advantage was the ability to include multiple perspectives on the wargamed situation. This approach also required additional effort to identify the most plausible outcome. Britain and Germany's processes reverted to free-form wargaming, which made wargaming easier for the commander but reintroduced the possibility of "subjective expert analysis bias", which had been so disastrous in the past.

Other differences continued to emerge over time. For example, the American approach emphasized developing optimal courses of actions based on enemy intent. It focused on the possible choices and motivations of an intelligent adversary. Conversely, the British and Germans used capability-based assessments, consisting of straightforward adversarial models, and they simply assumed that during a conflict adversaries would use all capable assets. For example, a German commander would use information regarding the enemy's capabilities to formulate his plan. Trying to discern the enemy's intentions was a secondary priority. Friendly-to-enemy force ratios were calculated, but the commander would mentally estimate conflict effectiveness of friendly-to-enemy interactions. Similarly, British commanders calculated friendly-to-enemy force ratios and estimated conflict effectiveness. However, the British replaced the discernment of enemy intentions with the identification of a most dangerous enemy COA.

Each change had its advantages and disadvantages, but all had unique potential to skew wargaming conclusions. Identifying enemy intent and a resulting course of action, if chosen correctly, has the potential to lead to better friendly outcomes. However, the danger with this approach is that predictions can be wrong and inappropriate action can introduce additional risk. Comparatively, the alternative capability-based approach suffers from the personal estimation of effectiveness. As in free-form wargaming, this methodology introduces the possibility of subjective expert analysis bias.

Like the British and German wargaming processes, the Soviet intelligence officer provided doctrinal information without participating in wargames. The Soviet process included consideration of the mission, instruction from superiors, and known factors, including available decision-making time, current friendly and enemy situations, and the capabilities of subordinate commanders. However, Soviet commanders used lookup tables to calculate capabilities of friendly and enemy units, whereas British and German wargaming estimated each conflict's effectiveness. Moreover, the Soviets assumed that their forces would have enough substance to fight through any conflict. Identifying enemy intent was ideal, but it was susceptible to deception and such analysis was limited by time.

Differing from the American wargaming process, British, German, and Soviet variants did not define specific wargaming rules. Of the 3, the German process was the most specific and included a 3-step process, comparing friendly and enemy combat effectiveness, examining changes in relative strength, and comparing friendly COAs to their chance of success.

On the other hand, the formalized MDMP became the surrounding context of American wargaming. The original MDMP was a 5-step process, first documented in 1932 (Michel 1990). In the 1950s, the United States adopted the staff function of wargaming, which included concepts from Game Theory and used concepts of rational actors with the goal of choosing optimal actions (Kretchik 1991, p. 15). In 1960, the MDMP expanded to include all command and staff actions needed to develop and execute a course of action (Shoffner 2000, p. 6).

In the 1960s, Soviet researcher Dr Lefebvre proposed the origins of what would become reflexive control theory (Thomas 2004). Reflexive control is an incremental adaptation to Game Theory. It observed the interactions of actors with their environments and suggested that one could influence the environment such that an adversary would willfully make a predetermined choice (Shemayev 2007). The Soviets began incorporating this theory into their wargaming and military decision-making doctrine as early as the 1960s. Soviet military interest further increased during the 1970s as 2 books were published, *Mathematics and Armed Conflict* and *Problems of Military System Engineering* (Chotikul 1986).

In this section, the historical evolution of wargaming illustrates the context of current Army wargaming. Historical examples, such as those demonstrated by GEN von Moltke and more recently during World War II, illustrate both wargaming utility and limitations.

2.6 Analytical Frameworks

The Army uses analytical frameworks to communicate assessments of the situation to and within tactical commands; for example, a PMESII assessment provided with an operations order. These analytical frameworks, while useful in describing the state of different situations, represent a structural representation of situations. However, the Army wargaming process uses data contained within analytical framework assessments as inputs to the interactive wargaming process.

Army Field Manuals advocate at least 3 analytical frameworks, which describe strategic, operational, and tactical situations. These frameworks include 1) political, military, economic, social, information, and infrastructure (PMESII); 2) area, structures, capabilities, organizations, people, and events (ASCOPE); and 3) mission, enemy, terrain, troops available, time, and civilian considerations (METT-TC) (HQ–DA FM 3-24.2 2009, p. 4–14; FM 5-0 2010, p. 1–5; ATTP 5-0.1 2011, p. 5–7). These frameworks encourage consistent and comprehensive communication between stakeholders at all levels and help them understand and communicate situations and environments. These methods also identify substeps within the larger analytical process. For example, ADRP 2-0, *Intelligence* (2012, p. 2-5) states one can use PMESII, ASCOPE, or METT-TC during the IPB, part of the larger MDMP.

2.6.1 PMESII-PT

PMESII, and its evolutionary descendent PMESII-PT, which adds physical environment and time, is a strategic and operational-level analysis framework. Currently, the Army uses PMESII-PT to convey an operational context and the understanding of a situation and mission to lower-level tactical commands (FM 3-24.2 2009, p. 1–3). Planners use PMESII-PT variables to describe the specific operational environment of operations (Hartley 2008, 2010). Tactical commanders receive PMESII-PT assessments from their higher-level headquarters and are responsible for translating them into relevant and actionable tasks.

The Army identifies and defines each of the PMESII-PT variables as summarized in the following (DA TRADOC G-2 2012, p. 55):

- **Political:** Describes the distribution of responsibility and power at all levels of governance—formally constituted authorities, and informal or covert political powers. It asks the questions, “Who are the tribal leaders in the village?” and “Which political leaders have popular support?” Subvariables include attitude toward the United States, centers of political power, type of government, government effectiveness and legitimacy, influential political groups, and international relations.
- **Military:** Explores the military and/or paramilitary capabilities of all relevant actors (e.g., enemy, friendly, and neutral forces) in a given operational environment. It asks the question, “What is the force structure of the enemy?” Subvariables include military forces, government

paramilitary forces, nonstate paramilitary forces, unarmed combatants, nonmilitary-armed combatants, and military functions.

- **Economic:** Encompasses individual and group behaviors relating to producing, distributing, and consuming resources. It asks the question, "What is the unemployment rate?" Subvariables include economic diversity, employment status, economic activity, illegal economic activity, and banking and finance.
- **Social:** Describes the cultural, religious, and ethnic makeup of an operational environment and the beliefs, values, customs, and behaviors of society members. It asks the question, "What is the ethnic composition of the operational environment?" Subvariables include demographic mix, social volatility, education level, ethnic diversity, religious diversity, population movement, common languages, human rights, centers of social power, and basic cultural norms and values.
- **Information:** Explains the nature, scope, characteristics, and effects of individuals, organizations, and systems that collect, process, disseminate, or act on information. It asks the question, "How much access does the local population have to the news media or the Internet?" Subvariables include public communications media, information warfare, intelligence, and information management.
- **Infrastructure:** Details the composition of the basic facilities, services, and installations needed for the functioning of a community or society in the operational environment. It asks the question, "What are the key modes of transportation?" Subvariables include construction patterns, urban zones, urbanized building density, utilities, and utility level.
- **Physical Environment:** Depicts the geography and manmade structures and the climate and weather in the operational environment. It asks the question, "What types of terrain or weather conditions in the area of operations favor enemy operations?" Subvariables include terrain, natural resources, and climate and weather.
- **Time:** Describes the timing and duration of activities, events, or conditions within an operational environment in addition to how various actors in the operational environment perceive timing and duration. It asks the question, "What is the cultural perception of time in the operational environment?" Subvariables include knowledge of the area of operations, cultural perception of time, information offset, tactical exploitation of time, and key dates, time-periods, or events.

In spite of the way it is currently used, the Army did not create the PMESII framework to communicate understanding. Rather, PMESII was designed to target nation-building systems and to address concerns that the existing ASCOPE framework was not sufficient (Ducote 2010, p. 6). At the operational level, PMESII-PT is a linear analysis tool that addresses "what" questions but does not answer "why" questions with respect to a complex environment. As such, the PMESII framework limits the level of understanding required by the recent Army Design methodology (McLamb 2009; HQ–DA ADP 5-0 2012).

2.6.2 ASCOPE

Compared to PMESII, which identifies operational- and strategic-level items of interest, the ASCOPE framework identifies tactical-level civil considerations. FM 3-24.2 (2009, p. 1–8) defines and identifies ASCOPE as a tool assisting counter-insurgent operations. Six categories make up its composition: areas, structures, capabilities, organizations, people, and events (US Army Combined Arms Center 1997). The Army identifies and defines each category as follows:

- **Areas:** Identifies geographical locations and regions of interest areas. For example, these areas could include political boundaries, social, political, religious, or criminal enclaves. It asks the question, "What is the relationship between people and where they live?"
- **Structures:** Identifies how locations, functions, and capabilities can either support or hinder operations. Traditionally, high-value structures include bridges, communications towers, power plants, and dams. Historically, significant sites include churches, mosques, national libraries, hospitals, cemeteries, historical ruins, religious sites, and other cultural areas. Other sites of interest have included jails, warehouses, toxic industrial materials, television and radio stations, and printing plants. It asks the question, "Why are the natural and manmade structures important?"
- **Capabilities:** Identifies the ability and effectiveness of local authorities or leaders to provide key functions and services. Priorities are ordered according to items necessary to save, sustain, or enhance life. Traditionally, public health, security, public works and utilities, economics, and commerce are included. It asks the question, "Who is capable and responsible for providing people basic services?"
- **Organizations:** Considers nonmilitary groups and institutions within the area of operations. Traditional types of groups have included tribes, political instantiations of insurgent groups, nongovernmental organizations, private companies, other government agencies, contractors, and media sources. It

asks the question, “What are the different groups of people in the operational environment?”

- **People:** Includes nonmilitary personnel whom military forces may encounter along with how and where each person communicates. Historically in the Middle East, this has included sheiks, city council leaders, imams, professionals, displaced persons, human sources, and tribal leaders. Forms of communication have included verbal, satellite, graffiti, and the Internet. Examples of meetings include gatherings at mosques, tribal council meetings, and cafes or teashops. It asks the question, “How do people communicate?”
- **Events:** Includes routine, cyclical, planned, or spontaneous activities. Examples have included elections, anniversaries, religious events, funerals, and political rallies. It asks the question, “When are events occurring?”

Both tactical and operational analyses are interconnected and related. For example, both ASCOPE and PMESII describe essential observables of a situation. Both frameworks help elicit situation conditions, which could cause the commander risk (Ntuen 2008; HQ–DA ATP 3-57.50 2013).

A helpful acronym of the ASCOPE Capabilities category is encapsulated by SWEAT-MS, which represents sewer, water, electricity, academic, trash, medical, and security (HQ–DA FM 3-24.2, 2009, p. 1–13; ADRP 1-02 2015). The acronym helps analyze personalities who control essential resources in a community. For example, the local government includes the mayor and council, who may in turn control the sewer. Historically, a tribal leader controls and protects water wells. In the Mideast, the government and imams influence academic curriculums. Private businesses and local merchants produce trash. Tribal doctors may provide medical assistance. Local police or tribal militia may influence local security.

Figure 11 displays an intersection of variables that influence both frameworks; PMESII variables are listed in the top row, and ASCOPE variables are identified in the first column.

	P Political	M Military	E Economic	S Social	I Information	I Infrastructure
A Area	• Enclaves • Municipalities • Political Districts • Shadow Government Area	• Areas of Operation • Areas of Interest • Safe Havens • Historic Ambush	• Industrial complexes • Farms & Livestock • Business Centers • Trade & Smuggling Routes	• Refugee Camps • Religious Sites • Neighborhoods • Boundaries of Influence	• Broadcast Area • Word of Mouth • Graffiti • Posters	• Commercial, Residential • Road Systems • Power Grids • Irrigation Networks
S Structures	• Courts • Government Centers • Meeting Halls • Polling Sites	• Bases, Airports, Naval • Police Headquarters • Known Leader Locations	• Banking • Fuel Distribution • Manufacturing • Markets	• Entertainment • Religious • Bars, Tea Shops • Schools, Universities	• Communications • Internet Service • TV Stations • Radio	• Emergency Shelters • Energy • Medical • Transportation
C Capabilities	• Dispute Resolution • Local Leadership • Public Administration • Political System(s)	• Doctrine • Organization • Training • Material	• Fiscal, Inflation • Import/Export • Withstand Drought • Raw Materials	• Medical • Social Networks • Academic • Tribal Structures	• Internet Access • Printed Media • Literacy Rate • Intelligence Services	• Clean Water • Construction • Communications • Sanitation
O Organizations	• Political Parties • NGOs • Insurgent Affiliations • Partnerships	• Host-Nation Forces • Insurgent Groups • Paramilitaries • Civic Organizations	• Banks, Business • Cooperatives • Labor Unions • Land Owners	• Clan, Tribe • Criminal Organizations • Religious Groups • Familial Organizations	• Media Groups • Religious Organizations • Insurgent Influence • Government Groups	• Service Providers • Government Construction • Private Construction • Law Enforcement
P People	• Political Leaders • Community Leaders • Judges • Prosecutors	• Key Leaders • Military Personnel • Insurgent Personnel	• Employers, Employees • Occupations • Merchants • Gang Members	• Community Leaders • Ethnic, Religious Leaders • Culture, Beliefs • Displaced Persons	• Decision makers • Media Personalities • Community Leaders • Heads of Families	• Subject Matter Experts • Builders • Development Councils • Road Contractors
E Events	• Elections • Significant Speeches • Significant Trials • Treaties	• Combat • Historical • Noncombat • Loss of Leadership	• Drought, Harvest • Labor Migration • Business Openings • Market Days, Payday	• Celebrations • National Holidays • Sports Events • Historical Events	• Disruption of Services • Religious Observation • Censorship • Publishing Dates	• Scheduled Maintenance • Natural Disaster • School Construction • Government Construction

Fig. 11 A crosswalk matrix between PMESII and ASCOPE variables. The figure illustrates examples of each variable combination.*

2.6.3 METT-TC

Acting in a complementary role to operational PMESII variables and tactical ASCOPE variables, METT-TC helps analysts to describe mission-specific variables. METT-TC is a framework that focuses on specific elements of an operational environment and how they might affect a mission (Baillergeon and Sutherland 2014). It identifies 6 variables: mission, enemy, terrain and weather, troops and support, time available, and civil considerations. The Army has identified and defined each of the METT-TC variables as summarized in the following (ADRP 5-0 2012, p. 1–9):

- **Mission:** Identifies variables in terms of impact on objectives and is the first variable commanders consider. It asks the question, for the given operation, "Who, what, when, where, and why?"
- **Enemy:** Identifies dispositions (e.g., organizations, strengths, locations, and tactical mobility), doctrine, equipment, capabilities, vulnerabilities, and probable courses of action. It asks the question, "What is the state of the enemy?"
- **Terrain and Weather:** Identifies terrain (e.g., rivers, mountains, cities, airfields, bridges) and weather features (e.g., visibility, wind, precipitation, cloud cover, temperature, humidity). The acronym OAKOC (Observation and fields of fire, Avenues of approach, Key and decisive terrain, Obstacles,

* Information and variables adapted from HQ–DA ATP 3-57.50 (2013, p. B-1 through B-8), Civil Affairs Civil Information Management, Appendix B, Civil Analysis Example of the Interrelationship of Operational Variables and Civil Considerations and, ATP 2-01.3 (2015, p. 4-29 through 4-35), Intelligence Preparation of the Battlefield

Cover and concealment) supports identification (Army ROTC 2008). It asks the question, "How will the environment affect the mission?"

- **Troops and Support Available:** Identifies the number, type, capabilities, and condition of friendly troops and support; includes supplies, services, and support of joint-military organizations, host nation, and partners. Support from civilians and contractors employed by military organizations, such as the Defense Logistics Agency and the US Army Materiel Command, are included. It asks the question, "What resources are available?"
- **Time Available:** Identifies the amount of time available for planning, preparing, and executing tasks and operations. This includes time required to assemble, deploy, and maneuver units in relationship to the enemy's location and other conditions. It asks the question, "When are the deadlines?"
- **Civil Considerations:** Identifies activities of civilian leaders, populations, and organizations. It asks the question, "How can the local population impact the success of the mission?"

Other analysis frameworks used in Joint Intelligence analysis include DIME-FIL (Diplomatic, Information, Military, Economic, Financial, Intelligence, and Law Enforcement) and JIPOE (Joint Intelligence Preparation of the Operational Environment). Both of these frameworks support recent whole-of-government approaches (Joint Special Operations University 2013).

DIME-FIL identifies the variables and national components of diplomatic, information, military, economic, financial, intelligence, and law enforcement (McDonnell 2009, p. 4; Shellman et al. 2011). These frameworks serve as coordination linkages between agencies with individual specialties so that they can participate in and contribute to overall objectives.

JIPOE is the joint-force's version of the IPB (Joint Chiefs of Staff 2013, p. I-17). Both frameworks help analysts to identify current and desired conditions, actors, actors' relationships, and their functions.

2.7 Challenges of Modern Wargaming

Despite the successful current state of wargaming and the value of the associated tools and involved processes, several challenges exist within the practice of wargaming. Challenges range from training to identification of enemy doctrine to individual participants' cognitive biases (US Government 2009; Hodge 2012; DA TRADOC Pamphlet 525-3-1).

One significant challenge of wargaming is the ambiguity in the knowledge, skills, and abilities (KSA) required for each role. For example, the relationship between the role of the Army's intelligence officer and the role play of the enemy commander is ambiguous. On the surface, this is a reasonable task; the job of the intelligence officer is to know the enemy. However, this is a naïve assumption; it does not communicate the experience or training required (DA 2014). For example, the further down the tactical chain of command, the younger the analyst is likely to be. In the worst case, it may be the analyst's first assignment.

Moreover, the hostile commander's culture influences perceptions, objectives, and methodologies. Assignments of intelligence analysts do not necessary consider this nuance. As such, even if an analyst is experienced, he or she may not have any familiarity with the culture or particular situation (Peck 2003; USAID 2006; Wunderle 2007; TRADOC Pamphlet 525-2-1; Salmoni and Holmes-Eber 2011).

Despite best efforts, the result of both scenarios is a naïve or biased and possibly misrepresented situation presented to the commander (Childs and Gallivan 2013). Unfamiliarity in any number of significant attributes can cause wargaming participants to become overconfident, misinterpret situations, or provide skewed results of actions, by either under- or overestimating capabilities or assets. However, in both scenarios, if appropriate KSAs were identified and participants were to meet stated qualifications, there would be less risk of wargaming conclusions being invalid.

A second challenge concerns the amount of rigor within current Army wargaming practices. Realities of a situation play a role during wargaming. Specific contextual situations may allow a minimal amount of time, such as planning for contingencies. The lack of appropriate or sufficient indicators of enemy intentions can reduce wargaming rigor. Moreover, the fog of war can cause the commander to focus on the wrong priorities.

Alternatively, minimally experienced personnel can result in low rigor. Research indicates that analytical methodology changes with the amount of experience analysts have. For example, when coming to conclusions, less experienced analysts seek to confirm information about their hypothesis. However, experienced analysts will seek information to disconfirm their beliefs.

As a result, there is a degree of variability in wargaming analysis. Army doctrine states that staff should evaluate at least 2 courses of action, the most likely and most dangerous cases. However, evaluating these 2 estimated situations does not demonstrate thorough analysis of the situation. Moreover, analysis of 2 courses of actions does not maintain the standards of rigor promoted by the larger intelligence community (ODNI 2015).

A third challenge concerns the knowledge of enemy doctrine and its application during wargaming. The practice of using enemy doctrine to inform wargaming analysis became popular while the possibility of conflict existed with the Soviet Union. During this time, Army doctrine writers assumed foreign military doctrines were appropriate expectations. However, adherence to stated doctrine may not be so rigorously applied in future conflicts. Recent state-on-state conflict has illustrated the willingness to create and implement hybrid warfare strategies, which purposely blurs lines between formalized and unconventional conflict (US Army Special Operations Command 2015).

Moreover, nonstate actors are an extension of doctrine ambiguity. In some cases, doctrine may not exist for nonstate organizational actors. A nonstate actor may not know what they will do until an action has actually taken place (DA TRADOC Pamphlet 525-8-5). Using doctrine helps wargaming participants to model the psychology of opponents, but when doctrine does not exist, predicting future actions may actually increase the risk of current practices (Robel 2004).

To model thinking opponents, current practice (based on principles of Game Theory) assumes rational actors. Justification for this assumption is reasonable in many cases; it is the desire to win the conflict. However, the theoretical rational-actor concept may not be an appropriate model in all circumstances, and other forms of actors, such as low-rationality actors, have emerged. Rational actors are a projection, a result of wargaming participants' individual perceptions, and may differ from reality (Axtell 2006a). For example, hybrid warfare takes advantage of this assumption by crossing limits and boundaries of social expectations and laws, while operating below the threshold of traditional war (Anderson et al. 2015; Moore 2015). In other cases, friendly and adversarial expectations, values, procedures, and objectives may differ in both interpretation and perspective; consider, for example, the use of suicide bombers as a military tactic.

Finally, wargaming is an evaluation and analysis of the interactions of many actors within the context of a course of action. Such interaction has the ability and tendency to exhibit emergent phenomena. However, it is difficult to use traditional deductive analysis to identify potential emergent phenomenon. Moreover, in situations of high uncertainty, wargaming provides little useful value. Thus, the best way to increase the rigor of tactical wargaming may be to identify and improve the process and methodology (and actual implementation) of wargaming.

3. Agent-Based Modeling in Tactical Wargaming

As described in the prior section, Army staffs at division, brigade, and battalion levels often plan for operations. As such, analysts consider the impact and potential consequences of actions taken. MDMP dictates identification and evaluation of possible enemy COAs; however, nonstate actors often do not exhibit the same level and consistency of planned actions that the MDMP was originally designed to anticipate. ABM and its resulting emergent behavior is a potential solution to model terrain in terms of the Human Domain and improve the results and rigor of the traditional wargaming process.

In this section, the report examines whether an agent-based capability can improve the MDMP process by providing additional rigor, speed, or flexibility during tactical Army wargaming. The study considers methodologies to improve analysis of the Human Domain, identifies a framework for modeling such a capability, and compares current Army wargaming practices with those if a hypothetical capability were to exist.

3.1 Agent-Based Modeling

ABM helps the modeler understand and simulate how a “whole of a system” responds to change over time. A complete agent-based model provides a fundamentally decentralized method of looking at the world where individual agents are instantiated within an environment and empowered to make their own decisions (Bonabeau 2002). While top-down or command-and-control relationships can be instantiated between agents in the system, ABM agents are fundamentally capable of autonomously making decisions without any centralized form of decision making or command and control (Odell 2002). Agents make their decisions based on their individual perceptions of other agents and their environment (Parunak 1996). Classic agent-based models run in simulated time and the system, analyzed as a whole, tends toward a steady state or falls into a predictable pattern of oscillating between extremes (Carmichael and Hadzikadic 2015).

Traditional model design and engineering techniques tend to focus on problem definition and decomposition for testing and design. Once the system goal is identified, engineers generally decompose larger problems into smaller, well-defined subproblems (Software Engineering Process Management Program 2010). Subcomponents are individually resolved by creating subsystems that act in predictable and controlled ways. Once engineers verify subsystems, they compose and integrate subsystems to create a composite system that solves the identified problem. Several factors influence the engineering process; for example, the degree of specification in the original problem will influence nature of the created subsystems. Other factors include the quality of verification and validation of individual subsystems. Numerous other aspects of the engineering effort, including planning, development, and configuration management, also contribute to the overall quality and value of the overall effort.

Creating an appropriate agent-based model requires a different style of engineering (Chaturvedi et al. 2004, 2008, 2014; Doursat et al. 2013). The difference between traditional engineering and creating agent-based models is analogous to the difference between structural and interactive complexity (DA TRADOC Pamphlet 525-5-500, 2008). Structural complexity is based on the number of parts within a system, the larger the number, the greater the complexity. Structural systems tend to exhibit the properties of linearity, proportionality, replication, additivity and repeatable cause and effect. A small input will result in a small output and a proportionally larger input will result in a proportionally larger output. It also means the system will respond the same, regardless of when input is stimulated. Finally, analysis of a structural system is valid; analysts can systematically evaluate progressively smaller components of the system for their properties.

Comparatively, interactive complexity is dependent on behavior of all parts and the resulting interactions between them; the greater the freedom of action for each part and the more linkages among them, the greater the interactive complexity (Chen 2011; Green 2011). However, analysis of individual components within interactive systems is difficult because interactive components do not exhibit the same properties as structural components (Crutchfield and Wiesner 2010). The ability of individual agents in an agent-based model to make “decisions” independent of the other agents can give the impression of instability and fragility. This is because each individual component, when duplicated and placed in an environment with other interactive components, tends to exhibit properties such as interactions, dynamics or flows, and temporal consequences (Bonabeau 2002).

Historically, differential equations have used model system dynamics (e.g., Monte-Carlo simulations) providing a predictable and repeatable way of looking at a snapshot of a system and perturbing initial conditions slightly to provide an estimate of the outcome. Unfortunately, using a single equation to model entire components of a complex system (e.g., population sentiment when the number of police increases in a nation-building context) tends to provide a false sense of clarity and predictability for system behavior that is significantly different from how events may evolve in the real world (Bonabeau 2002; Helbing and Balietti 2011). ABM provides a more flexible and adaptive framework to tease out of the complexity of nuanced and unpredictable elements of a system by allowing decomposition of such complex systems into smaller subsystems with individual, often stochastic, simulated decision behavior.

To develop an agent-based model, the modeler creates a set of heterogeneous agent types with their own rule sets, and places instantiations of these agents into an environment (Bonabeau 2002). Modeling emphases is on creating and altering rules of individual agent types rather than identifying and creating rigid system-level interactions. Each agent has the ability to exist in one or more states, to represent fundamental shifts in behavior or interact with the environment. Additionally, agents have a state-based “decision-making” ability constructed as a set of mathematical equations to represent some level of decision-making capability or artificial intelligence. Depending on the level of system decomposition, this set of equations may capture complex decisions (e.g., whether or not a person should organize a riot) or simple decisions (e.g., should the agent look for a food source).

Depending on the instantiation of the agent, each instance may have slight differences in their characteristics governed by an initial distribution (e.g., height variation in a population). Additionally, each rule has a probability distribution attached to it, which is used to determine whether rules are invoked (e.g., will a person respond violently to a perceived threat). This provides a method of capturing outcomes or behaviors that are outside of the scope of the model, or that may be too complex to replicate, given the current understanding of the real-world equivalent. The use of varying initial conditions/parameters for decision-making structures of each instantiated agent ensures variance within the totality of systems’ agents’ choices (Miller 1996; Barry and Koehler 2004; Nakayama 2012). Once an iteration of the model is complete, the modeler simulates and evaluates whether changes result in an appropriate outcome. The term “appropriate outcome” is used because model output is not precise and is represented by a possible representation of the output. By analogy, in programming, the equivalent is compiling and testing source code whereas in modeling, it is instantiating a set of agents with random initial conditions and running a Monte-Carlo series of tests evaluating whether expected system phenomena is observed at various points in simulation time.

ABM works comparatively well when compared to average or Gaussian statistical techniques because individual agents can exhibit different types of logic, for example, individualized preference for decision-making thresholds, different degrees of rationality, conditional rules, and use of memory and learning. Similarly, in the context of agent interactions, communication networks where all agents are not fully connected are another situation where ABM can simulate emergent phenomena. Both types of situations are common in social situations and ABM can model these situations.

3.2 Identify Rigor

Traditional structured problem solving and resulting engineering generally creates precise solutions. However, most situations the Army deals with are not precise or structured. Rather, interactive social systems strongly influence outcomes of Army missions; for example, friendly personnel, adversarial personnel, noncombatant personnel, the civilian population, and the resources they use, control, and affect. As such, emergent situations and outcomes regularly occur. Given this context, an agent-based capability could improve the rigor of tactical Army wargaming. However, 3 points are necessary to support this argument. First, identify a comparable baseline of rigor for wargaming and ABM, independently from each other. Second, examine the applicability of ABM to wargaming and determine whether its application can increase wargaming rigor. Third, determine whether application of ABM is possible at the tactical level and if so, what it might look like.

Generically, rigor is the quality of being extremely thorough, exhaustive, or accurate (Oxford 2016). Alternatively, rigor is a function of the quality of thinking, not the quantity (Rand and Rust 2011). High expectations are important and include effort on behalf of the learner. Often, deep immersion in the studied topic includes the context of real-world settings and working with an expert. Generally, it includes depth or care of study, and use of a process, such as the scientific method, to evaluate hypotheses. It may also take the form of a thoughtful literary analysis, with sufficient depth and attention to detail and accuracy (Department of Instruction 2011).

Army doctrine writers have embodied and applied rigor throughout the wargaming process, while trying to keep it flexible and adaptable to a variety of unanticipated scenarios. For example, the MDMP process contextualizes wargaming within its larger 7-step process, which tasks and integrates activities of all stakeholders. Staff thoughtfully considers future decision points and links them to a synchronization matrix; together, both the MDMP process and synchronization efforts balance individual warfighting functions. As staff analyzes a given course of action, they identify and record strengths and weaknesses. These observations empower staff to make unbiased analyses, interpretations, and decisions regarding findings.

However, based on the authors' observation of Army wargaming, the practicality of tactical wargaming is not as rigorous as stated in doctrine. Many times, there is limited time available for a proper application of the MDMP and its substep wargaming process. The authors understand this is a reasonable and expected military condition but its consequences lead to less analytical rigor. In another example, doctrine identifies a number of roles and stakeholders who should participate in wargaming. However, in tactical situations, not all identified people can participate because some roles do not exist at lower levels of tactical command. For example, only the S2, S3, and S5 (i.e., intelligence, operations, and plans, respectively) officers may be involved in wargaming. In this case, civil and other local population perceptions and biases may not be fully considered. In general, doctrine broadly applies rigor to the Army wargaming process, but in certain cases, implementation is not realistic to the extent described.

In practice, commanders require 2 COAs to be identified and wargamed: the most dangerous and most likely. Unfortunately, 2 scenarios are likely too few options to evaluate situations broadly, especially in an interactively complex situation. Using a small number of possibilities (i.e., COAs) to make a decision is a common decision-making mistake. Similarly, making judgments based on how easily information is accessible, or for expected situation outcomes, decreases decision-making rigor. People are often overconfident in their beliefs, assuming what they believe will happen more often than it actually does (Kass 2002). Together these biases increase variance in the rigor that wargaming provides to the commander.

Finally, creating and analyzing courses of actions based on assumed enemy courses of action increases the potential for overly risky consequences. As discussed in Section 2, there are 2 major methods of developing courses of action. The first is a traditional capabilities-based method that uses intelligence to ascertain adversarial assets and capabilities. Wargaming helps identify whether identified capabilities affect that particular friendly course of action and if so how. The second method is to identify adversarial assets, capabilities, and intents and develop courses of action that embody adversarial intents (Caffrey 2000). Using the second method, if staff identifies adversarial intent correctly, there is a theoretical chance of a better friendly outcome. However, if staff chooses incorrectly, the risk to a positive friendly outcome can be higher than using the first method. The Army endorsed the second method after World War II, once conflict with the Soviet Union became a possibility. Staff used their perception of Soviet doctrine as the basis for identifying adversary intent. However, nonstate actor doctrine is less formal and may be nonexistent; a prescient and decision may not exist, right up to the actual decision and subsequent actions occur. Moreover, recent history and actions of both state and non-state actors seem to contradict expectations of knowing preaction intent.

ABM rigor depends on what the modeler is looking for, specifically, in correlation with the asked question and nature of the solution desired. For a simple model, the modeler calibrates model output to observed data and uses scale normalization to estimate an interpretation of model output. Interactions between the models' agents drive output and feedback loops that control the resulting emergent properties (Heylighen 1999). In a more complicated case, creating a simple model is still the likely starting point. Once an initial model is working as expected, the modeler slowly increases the complexity by adding additional agent types, rules, probability distributions, and interactions. Complex models are simulated just like simpler cases but are compared quantitatively to collected data that helps evaluate whether the model represents the real world.

Since modelers can develop a wide range and variety of models, a common evaluation framework would help define criteria used to describe the rigor of individual models. In the mid-1990s, Drs Rob Axtell and Joshua Epstein proposed an evaluation framework to provide such guidance (Axtell and Epstein 1994). The evaluation framework graded models at 4 progressively difficult levels of maturity and rigor. Level 0 models produce a caricature of reality allowing a user to visualize agent motion. A Level 1 model produces qualitative agreement with empirical macrostructures and suggested verification by plotting distributional properties of the agent population. Level 2 models produce quantitative agreement with empirical macrostructures, as established through statistical estimation. Level 3 models exhibit quantitative agreement with empirical microstructures, as determined from cross-sectional and longitudinal analysis of the agent population. Using this framework, one can identify the rigor an individual agent-based model provides.

The study suggests if a modeler can describe and model human interactions abstractly, in a way that is effective for Army wargaming, then using the abstract model to evaluate individual circumstances will provide a more rigorous approach to enemy perception than evaluation by intuition (Beeker et al. 2010). Consistent use of a model is a technique to limit the impact of psychological biases on decisions including biases of anchoring, overweighting, and order of evaluation (Kass 2002). Moreover, consistent with the definition of rigor, even if a novice is using the agent-based capability, an expert has built the utilized model in the first place. If the novice is using the model in a realistic setting and the user is working with an expert, via the model, then both attributes are consistent with the definition of rigor and the overall result is an increase in wargaming rigor.

3.3 Model of the Human Domain

Special Operations Command (SOCOM) and its Army variant, Army Special Operations Forces (ARSOF), have identified a fundamental shift in the character and nature of warfare that involves a shift toward irregularity, hybridity, and diversification of participants and threats. As such, ARSOF may be responsible for future hybrid campaigns mixing conventional, unconventional, and cyber that could influence operations through relationships with local security and governance

(Ryan 2014; Raymond 2015). That said, there is a need to understand the local population within the context of the operational environment to take appropriate action to influence human behavior toward intended outcomes (Coles 2006; Franks 2013; Brecher 2014). Similarly, the Army needs to understand dynamics of civil populations within the context of it missions to be able to effective execute the wargaming portion of the MDMP (Joint Chiefs of Staff 2015a).

Human Domain is a concept SOCOM proposed to focus on people as individuals, groups, and populations who exercise agency within an area of operation in a way that can affect the US, Partner, or adversary interests. It is composed of 5 elements that represent attributes of human decision-making and behavior and provide insight into the local culture. These 5 elements are social, cultural, physical, informational, and psychological, each with subelements specific to their designation (Brecher 2014). The Human Domain concept is a work in progress and proposes a comprehensive discipline to identify, understand, and influence relevant individuals, groups, and populations across the range of military operations. The social element describes the structure and relationships among groups and institutions, involving competition and efforts to impose interest and perspectives (MacCalman et al. 2013). The cultural element involves the impact of a society's beliefs, customs, and way of life on people's behavior. The physical element is composed of how the natural and manmade worlds shape individual actor's priorities. The informational element is composed of information sources, availability, and substance of data. Finally, the psychological element identifies how people evaluate and act upon information, including patterns of judgment and reasoning in response to available facts.

To begin improving the rigor of modeling human behavior, the authors believe the Human Domain concept is a good starting point. It appropriately identifies major-need categories and identifies relevance between military objectives, conflict, and the larger contextual perspective of the local population. However, the authors believe the Human Domain concept is a structural representation of the problem and is more appropriate as a set of requirements rather than a model. To model emergent human behavior, instances of agents need to interact with each other and their environment.

3.4 Social Cognitive Theory

In the 1980's, Dr Albert Bandura (1999) proposed an agentic model of human psychology and behavior that he termed Social Cognitive Theory (Pajares 2002; Matei 2010). Since then, he has clarified his theory in a series of papers and books for over 30 years. Social Cognitive Theory expresses individual human agency using 3 components: agent state, behavioral patterns, and the environment. Agent state embodies motivation, affective cognition, and biological attributes of individual actors. Symbolic modeling, adoption of determinants and social network diffusion, encompasses behavioral patterns. The environmental component is composed of imposed environmental constraints, selected environmental aspects, and constructed attributes. The authors suggest this theory is an appropriate theoretical starting point to model the Human Domain and maps directly to the ABM paradigm.

Figure 12 illustrates the similarity and difference between the Human Domain concept and the Social Cognitive Theory. In general, the Social Cognitive Theory identifies each of the major Human Domain elements. However, an emphasis of several Human Domain attributes includes those at the group or high level of aggregation. While Social Cognitive Theory identifies application to agentic-groups, the authors suspect this aspect may need additional investigation and specification to model appropriately. Additionally, interaction and behaviors of economic activity may also be an area of additional specification. However, in general, it appears Social Cognitive Theory is a reasonable starting point and abstract model applicable to the Human Domain.

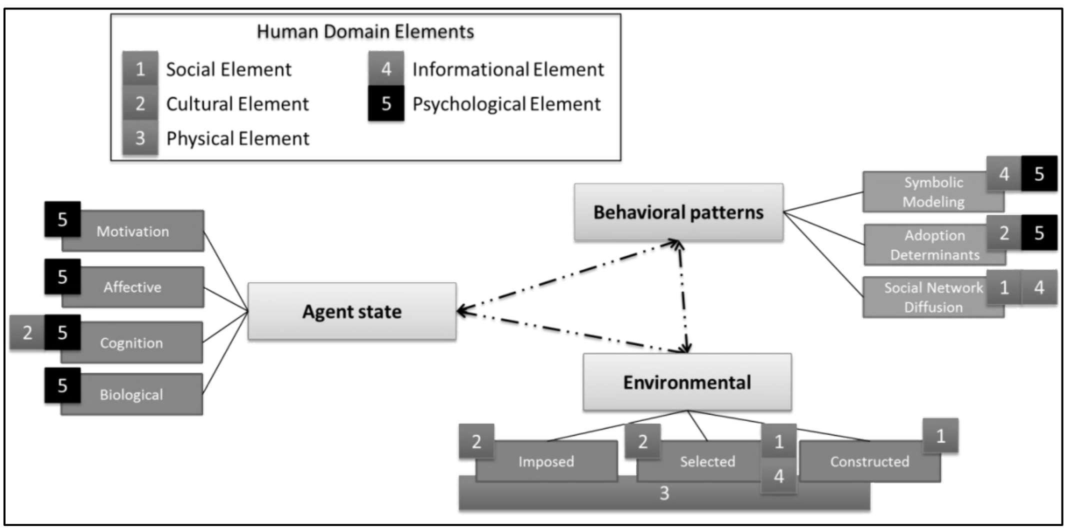

Fig. 12 This figure illustrates Social Cognitive Theory in its triadic reciprocal state. The Human Domain concept is compared to and overlaps with Social Cognitive Theory. Both theories describe the same concepts, but Social Cognitive Theory offers an agentic form of interactive complexity.

3.4.1 Environment

The environmental component is a dynamic representation of the agents' environment and is composed of 3 aspects. The first aspect consists of imposed circumstances such as the agent's social structure, including family, clan or tribe, and government. Imposed physical environment includes conditions such as the terrain, communications, and war zones. The second aspect is selected environmental aspects including agent associations, activities, and surroundings. The agent also selects the social environment and nature of cultural of interactions. The third aspect consists of constructed environmental conditions; this includes the social environment and created economic or monetary resources.

3.4.2 Behavior

Agent behavior also is composed of 3 aspects. The first aspect is a symbolic model, which embodies the knowledge structure, or process models, roles, and strategies representing learned processes. Different styles of thinking form these knowledge structures; for example, behaviors modeled by other agents, the outcome of exploratory activities, and verbal instruction. Bandura suggests learned behavior is the result of a cognitive synthesis process resulting from acquired knowledge and influences by observations and behavior modeled by other agents.

Adoption of behavioral determinants is the second aspect. The agent's perception of its own self-efficacy to master requisite competencies influences whether the agent adopts certain behaviors. Agents adopt behavioral patterns based on perceived costs and benefits resulting from such actions. As such, an agent may learn a new behavior but may never use it because of perceived impediments. Similarly, agents use opportunity derived from behaviors to estimate the cost and benefits of actions.

The third subaspect is the diffusion of social networks. Psychosocial factors influence diffusion, structural interconnectedness, and interaction of the agents' social network.

3.4.3 Agent State

Agent state is the internal representation and perception of each agent and is composed of 4 sub-aspects: motivation, cognition, affective and biological. The first aspect is motivation, which is composed of a process consisting of personal challenges, then feedback or evaluation of performance, and finally a self-influence cycle. Goal setting is a primary influence on motivation and results in a set of hierarchically structurally goals. These aspirations are the result of efficacy beliefs, which are products of expectancy, resilience, and thresholds to settle for outcomes not fully meeting objectives. Motivation also helps regulate activities by using forethought or projected future situations. Agents examine plausibility by considering likely consequences of actions, setting goals and planning courses of action. Agents also evaluate planned courses of action by considering the potential to produce desired outcomes while avoiding detrimental outcomes.

The second part of agent state involves the cognitive aspect of the agent state. It guides the reasoning processes by using a combination of conception matching, perceived level of skill and translation of conception to actions. The conception matching process includes corrective adjustments, standards, and actions. Differences in perceived levels of skill both constrain and generate different situational conditions. Finally, the conceptualization process includes a feedback process that included detecting and correcting mistakes. The cognitive aspect also includes enactive experiences, social guidance, and modeling influences.

The third part of agent state is the affective attribute that contributes to expressing emotion. An example of an emotion is depression, which is a result of low perceived efficacy and unfulfilled aspirations or devaluation of attainments that helps weaken the efficacy cycle. Coping efficacy is an ability of the agent to transform the threat environment to a benign circumstance. It also helps to lower the agent’s stress and anxiety levels. Mitigation is a function of the agent’s coping efficacy; if the agent cannot cope, alternative means to deal with the situation include relaxing, engaging in activities, receiving assurance from friends and family, and think reassuring thoughts. Depressing trains of thought are the responses to rejection, loss, failure, or setback. Depression also is a function of the agents’ supportive relationships, if a low sense of social efficacy exists. However, the agent can overcome depression by modeling affective strategy, demonstrating perseverance, positive incentives, or availability of other resource to support efficacy.

The fourth part of the agent state is the biological attribute. While Social Cognitive Theory identifies a biological component, it does not sufficiently identify constitute components. Perhaps a logical application of biological attributes is modeling the interconnection between physical skill, agent state, and behavior.

3.5 Applicability of ABM to Wargaming

Army missions range in breath of objectives, from offensive to defensive to civil support. At the tactical level, wargaming personnel often focus on maneuvers and force-on-force considerations. However, during recent years counterinsurgency circumstances have forced personnel to consider the impact of direct interpersonal interactions with the local populations. In this section, the study examines applicability of ABM to wargaming and determines whether its application could increase wargaming rigor.

Wargaming staff and intelligence-analyst colleagues use different forms of analysis in their consideration of the battlefield, including the contextual physical and human terrain (Hanratty et al. 2014; Herbert 2014) . Intuitive analysis, case-based reasoning, game theoretic methods, and critical factor analysis are examples of several analytic forms. Intuitive analysis and informal application of induction is among the most popular and commonly used methods of intelligence analysis (Folker 2000). Intuition is a feeling or instinct that does not use a demonstrative reasoning process, and analysts may not be able to explain their theory with available evidence.

Case-based reasoning, or solving new problems based on solutions of similar past problems, is another common and intuitive method. However, this method is slightly more rigorous in that it is composed of 4 steps. The first step is retrieving cases relevant to solving the problem. Second is translating solutions from prior examples, adapting the former solution to the current problem. Third is testing the modified solution to the current problem and revising as appropriate. Fourth, once the solution is successful, is storing the resulting solution as a new case to draw upon in the future (Kolodner 1992).

Game Theory is a technique that is more rigorous and involves analyses of players' decision-making and choices, which can potentially affect interests of other players during conflict or cooperation (Turocy 2002; Price 2003). Complementary to Game Theory is a selection methodology, which is applicable to the decision-making process involved in selecting a course of action; these are the maximin and minimax selection heuristics discussed in Section 2.

Another structured form of analysis is Critical Factors Analysis, otherwise known as Center of Gravity and Critical Vulnerabilities developed by Dr Joe Strange (Strange 2005; Strange and Iron 2004) in the 1990s. The Army adopted this form of analysis at the strategic level and used the term "decisive points" to attack enemy Centers of Gravity. Center of Gravity analysis as an extension of traditional Clausewitzian war theory to help communicate military objectives and is used to communicate the Army operational design and planning process (Rueschhoff and Dunne 2011). Center Factors Analysis is an analysis of the progression of dependencies: 1) Center of Gravity, 2) Critical Capabilities, 3) Critical Requirements, and 4) Critical Vulnerability. By analyzing the enemy and its Critical Capabilities, one can identify the chain of dependencies from Center of Gravity through Critical Vulnerability. If one can destroy a Critical Vulnerability, then the enemy will both lose Critical Capabilities and degrade the power of the Center of Gravity (Schnaubelt et al. 2014).

Figure 13 illustrates interaction between Social Cognitive Theory and Center of Gravity Analysis; the technique can describe individuals and social groups but in this case, the study focuses on the interaction from the perspective of an individual. The figure describes an arbitrary Center of Gravity; it could be an agent or another notional item. However, the Critical Capabilities are those behaviors the agent possesses. Furthermore, both the agent's perceived efficacy and the perception of the agent's efficacy of such behavior affects the value and effectiveness of the Center of Gravity. Critical Requirements are composed of the agent's environmental factors; some factors are imposed, while the agent chooses and constructs others. Both physical resource and notional items, such as social networks or monetary resources, are part of the selected and constructed environment. Finally, the figure describes an arbitrary Critical Vulnerability but could, as an example, overlap with environmental items friendly forces has access to.

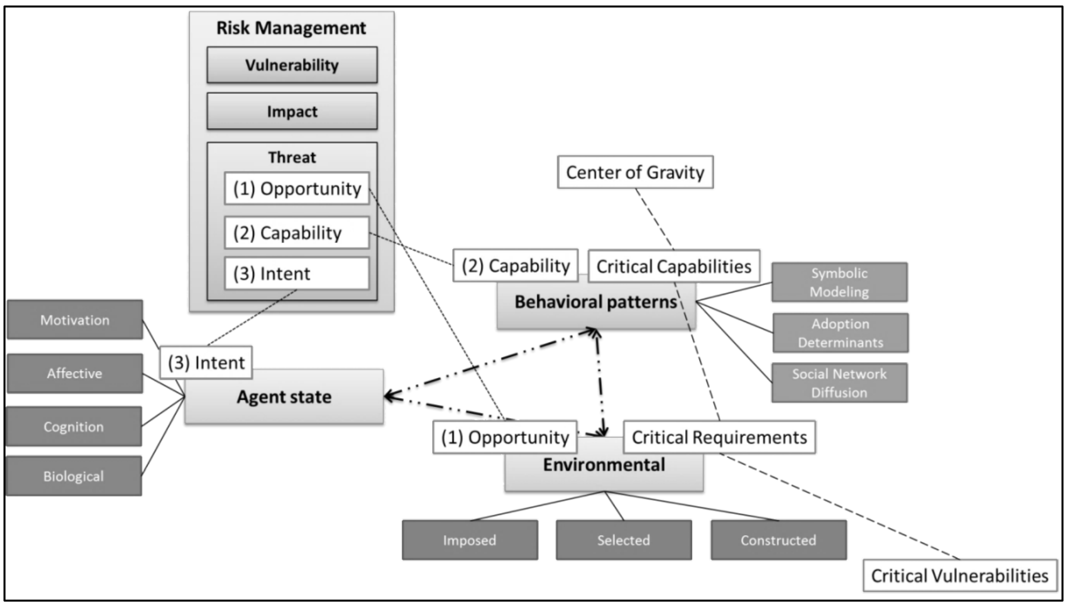

Fig. 13 This figure illustrates Social Cognitive Theory and the overlap between Risk Management and Critical Factor Analysis methodologies. Similar to Fig. 12, each methodology overlaps, but Social Cognitive Theory offers a more comprehensive expression of the interactive complexity.

Formalized risk assessment is another structured form analysis and approaches individual risks or problems from the perspective of plausibility to affect to the whole system (DHS 2010). This form of analysis attempts to understand the systematic nature of each problem and make an informed assessment as to the consequences that could result. Analysts using this method decompose each identified risk into 3 primary parts: vulnerability, impact, and threat (Cloppert 2013). Vulnerability is the exposure to the risk. However, vulnerability is changeable and specific to time; stakeholders can reduce vulnerability. Impact is the realized result of risk. Threat is a component of risk that is potentially discoverable by using intelligence and composed of 3 aspects: adversary opportunity, adversary capability, and adversary intent. The adversarial actor controls intent, and is similar to the previous discussion of enemy courses of action. Opportunity relates to the timing and knowledge of the adversary. Capability describes the ability of the adversary to achieve intended goals and opportunities and is analogous to possible enemy capabilities-based courses of actions. In addition, adversary skills and resources influence capability.

Figure 13 also illustrates the interconnection between Social Cognitive Theory and risk management, specifically the "Threat" section of model, which represents the interaction between the specific risk and external agents. External agents are, in this case, any agent operating within the simulated agent-based model. Risk opportunity models the environmental factors in the simulated model. Agents' physical constrains are limiting factors. For example, access for a physical space or possessing appropriate resources to enable access to the identified risk. Risk capability is a manifestation of an agent's behavioral patterns. Efficacy of an agent's skills and learned behaviors act as constraints on the number of agents who could plausibly affect the given risk. Lastly, risk intent is modeled by agents' self or mental state.

The intersection of Social Cognitive Theory, Risk Management, and Center of Gravity Analysis illustrates the interconnection between the described modes of analysis. It identifies that an agent-based model is a generic enough technique so if a modeler describes an appropriate model, the technique can notionally represent equivalent results as those resulting from structural analysis approaches. However, while an equivalent agent-base model could provide analogous result, it does not necessarily mean an agent-based model could increase the rigor of wargaming.

Each of the aforementioned techniques have different emphasizes on interaction and plausibility. Similar to Game Theory, ABM represents actors and their environment from an interactive perspective. This allows for the case of unexpected but emergent results of actions taken. Additionally, these findings suggest an appropriate agent base model can represent the emphasis and attributes of each structured analysis technique; specifically, the agentic form of Social Cognitive Theory model discussed in the previous section.

3.6 Identifying an Increase in Wargaming Rigor

Sensemaking is a technique to examine an arbitrary piece of analysis and determine the rigor of a product. David Moore (2011) proposed the idea in his book titled *Sensemaking: A Structure for an Intelligence Revolution* when he examined several types and instances of intelligence failures along with the current practice and challenges of intelligence analysis. In his book, he adopted a series of eight metrics proposed by Zelik, Patterson, and Woods who proposed, in their 2007 paper titled

"Understanding Rigor in Information Analysis", that rigor applied to information analysis is an assessment of process quality, affording communication about the process, rather than the product, of analysis (Zelik et al. 2007). In other words, rigor represents a mechanism, which reveals the observability of analysis (Woods et al. 2002).

The 8 metrics of rigor were Hypothesis Exploration, Information Search, Information Validation, Stance Analysis, Sensitivity Analysis, Information Synthesis, Specialist Collaboration, and Explanation Critiquing—necessary attributes of rigorous analysis. They define each of these 8 metrics as the following (Zelik et al. 2009):

- **Hypothesis Exploration**: Constructing and evaluating potential explanations for collected data
- **Information Search**: Focused collection of data bearing upon the analysis problem
- **Information Validation**: Critically evaluating data with respect to the degree of agreement among sources
- **Stance Analysis**: Evaluating collected data to identify the relative positions of sources with respect to the broader contextual setting
- **Sensitivity Analysis**: Evaluating the strength of an analytical assessment given possible variations in source reliability and uncertainty
- **Information Synthesis**: Extent to which an analyst goes beyond simply collecting and listing data in putting things together into a cohesive assessment
- **Specialist Collaboration**: Extent to which substantive expertise is integrated into an analysis
- **Explanation Critiquing**: Critically evaluating the analytical reasoning process as a whole, rather than in the specific details

In *Sensemaking*, Moore applied these metrics to evaluate strategic analysis products. He compared a National Intelligence Estimate example to 2 other similar versions, one academic and the other created with the assistance of a software tool. He found no one report satisfied all 8 criteria of rigorous analysis. However, the combination of the 3 reports resulted in the most rigorous analysis.

Wargaming is the analysis of several independent courses of action. As such, wargaming is an information-based analysis process. Therefore, the 8 attributes of analysis rigor apply to wargaming, regardless of whether analysis is strategic, operational, or tactical. Using these criteria, Table 1 illustrates an evaluation of whether a hypothetical wargaming situation would benefit from an agent-based capability and if so, how might these benefits realized. To apply these attributes, the study uses evaluation criteria identified in Zelik, Patterson, and Wood's (2009) paper, "Measuring Attributes of Rigor in Information Analysis".

Table 1 The result of using the 8 metrics of rigorous analysis to identify an estimated level of rigor in wargaming analysis. The left column is an estimation of wargaming rigor at the tactical level, as is currently done. The right-hand column introduces a hypothetical agent-based capability, which in this report is purposely under-specified; however, estimated level of rigor is used to illustrate the plausibility of improved rigor and the areas where such a capability would be most useful.

Metric of rigor	Current Army wargaming	Estimated value to Army wargaming derived from a hypothetical agent-based modeling capability
Hypothesis exploration	**Low**: there is little consideration of alternatives; standard practice is identification of most dangerous and most likely course of action	**Low**: little direct value from agent-based capability; alternate value could be derived from automated reasoning or other automated monitoring and alerting
Information search	**Moderate**: at the tactical level, time, level of access, and connectivity are all issues and realistically prevent exhaustive searches	**Low**: both user and reach-back support are required to develop and find appropriate information
Information validation	**Low/moderate**: general acceptance of information with healthy amount of consideration as to the trustworthiness of reports of the local population	**Low**: validation of models and interaction between actors will help improve validation outcomes
Stance analysis	**Low/moderate**: incorporates basic comparison strategies but includes western-society biases in consideration	**Moderate**: breath of Human Domain attributes helps discern perspective but is largely dependent upon the user
Sensitivity analysis	**Low/moderate**: evaluation of several courses of action helps consider alternatives and identify boundaries through decision points.	**High**: computationally running many orthogonal configurations and scenario permutations can help the user identify sensitivities and decision points
Specialist collaboration	**Low/moderate**: minimal direct collaboration with experts but interaction of local population draws experience from local social networks	**High**: verified and validated agent-based capabilities had a specialist involved during vetting process ensuring micro- and macro-behaviors
Information synthesis	**Low/moderate**: depicts events in context of 6 warfighting functions but lacks efforts to evaluate longer-term consequences	**High**: breadth of considerations are involved and described to the user, helping provide context and insight into consequences
Explanation critiquing	**Low/moderate**: reliance on pre-existing modes of critiquing, such as supervisory, but alternative views incorporated from new personnel participation	**Moderate**: agent-based capability helps ensure many perspectives are incorporated, availability of verified and validated models is essential

In reviewing Table 1, several attributes indicate an agent-based capability could improve rigor of wargaming; these are rows where the "estimated value" column has a higher utility than "current" column. Any single row where the value column is greater than the current column is sufficient to identify the possibility of improvement. Therefore, this suggests an agent-based capability could increase the rigor of Army wargaming in several aspects. Moreover, value provided from a hypothetical agent-based capability is concentrated in analytical areas that are among the most difficult for wargaming participants to do themselves, especially when significant time constraints or external situational pressure exists.

3.7 Tactical Agent-Based Wargaming

Tactical missions range in variety and breadth, from kinetic to stability to civil support operations. Kinetic actions may be necessary in a variety of situations but, in and of themselves, may not be sufficient to resolve conflict and fulfill political objectives. MG Flynn said, “Simply stated, the lesson of the last decade is that failing to understand the human dimension of conflict is too costly in lives, resources, and political will for the Nation to bear” (Flynn et al. 2012). Similarly, the United Kingdom’s (UK’s) Foreign Secretary David Milliband recently stated, “The lesson is that while there are military victories there is never a military ‘solution’. There’s only military action that creates space for economic and political life.” Moreover, in the Human Domain, “tribalism is underneath everything; every glance, every knowing look, every payment, every invitation, everything that happens is linked to tribal connections” (Stewart 2013). In this section, the study examines whether application of agent-based modeling is appropriate at the tactical level and, if so, what it might look like (Berzins et al. 1999).

The Army’s experience during the Iraq and Afghanistan conflicts illustrated military intelligence personnel are not prepared to read or analyze the cultural terrain of the population. As such, without abandoning core warfighting capabilities, is it appropriate to view cultural terrain as a necessary parallel endeavor (Connable 2009)? Alternatively, does it make sense to use an agent-based capability with time constraints imposed by tactical contexts? Would a tactical agent-based capability provide value during wargaming, by either providing additional insight or by identifying risk-based decision points during identified courses of action? Finally, would nonexpert users be able to use and interact with the capability?

Recent conflicts, including those in Iraq and Afghanistan and others throughout the world, have demonstrated adversaries continue to evolve the form of warfare. An example of this evolution is so-called Hybrid Warfare, a technique that employs individual aspects of political, military, economic, and criminal tools together in such a way that the overall conflict stays below the threshold of conventional war (Joint Chiefs of Staff 2015b). As this form of warfare changes, it is possible that future international relations could be characterized by continuously shifting combinations of collaboration, conciliation, confrontation, and conflict (Brecher

2014). However, in some published examples of practical application of MDMP, staffs demonstrated an inability to use cultural terrain to their advantage, resulting in missed opportunities combating insurgencies and terrorist operations (Connable 2009).

ABM has the potential to improve a spectrum of tasks related to MDMP and wargaming. One example includes how using an agent-based capability could help understand consequences of the local population's cultural terrain by helping to mitigate some documented failures. In the future, success of upcoming deployments in populated areas is likely to depend on both social and combat considerations. For example, local biases and decision-making processes are social interactions that are likely to be undervalued during traditional wargaming. Moreover, local perceptions to Army forces are likely to be different from those projected and an agent-based capability could help identify unexpected consequences or local-population reactions.

Based on prewar tables of organization and service staffing, there simply were not enough trained and experienced Foreign Area Officers (FAOs) to support each brigade (Connable 2009). An agent-based capability could act as an independent perspective during wargaming, assisting in what would normally be the FAO's responsibility but without saddling the Army with the burden of ensuring enough FAOs are available for all parts of the world. Using an agent-based model, acting in this type of capacity could help ensure civil inputs, interactions, and consequences were available and considered down to brigade-level wargaming.

Alternatively, an agent-based model could assist in population engagement, helping to ensure proper interaction with the local people. One engagement with the local population that led to successful execution and mission objectives was in Al-Anbar where, as early as 2004, Marines who were formerly ill-prepared for cultural terrain began to engage with the local tribal, religious, and business leaders (Connable 2009). They conducted census polling and gathered cultural inputs from patrol reports and human-intelligence sources. From this collected information, they developed specific and local messages meant to engage the population. After engaging and interacting with the population for several years, violence within Al-Anbar, Iraq was substantially reduced and was eventually returned to Iraqi control. Integrating ABM in this process would provide a standard tool for inputting that information and providing a model of how the population may respond to different threats and interventions.

3.7.1 Using an Agent-Based Capability during Tactical Wargaming

Usability of an agent-based capability in a tactical environment is a realistic concern. To be relevant to a nonexpert user, the agent-based capability would need to be simple yet configurable enough to allow a 20-year-old intelligence analyst to adjust relative impacts of cultural variables, while operating within the context of a friendly COA. Wargaming participants would need to be able to amplify or reduce behavioral nuances of the population to explore a number of “what if” scenarios. For example, consider the following:

> Imagine the US was about to engage peoples in 3 northern Afghan Provinces in 2010 after ignoring their plight up to that point. No resources have been committed to the Northern provinces during the war. Intelligence analysts have learned from interrogations, cultural studies, ethnographic studies, lessons-learned from Russia's interaction with them during the 1980’s, and open sources that the northern Uzbeks and Tajiks have learned not to take sides until resolution is imminent. However, the US has reason to believe that Uzbeks and Tajiks are not happy about their subjugation to the Quetta and Peshawar Shuras. Even if they wanted to fight the US and Afghan government forces, they are limited in the ability to collect zakat, recruit suicide bombers, recruit, move, and train IED (improvised explosive device) emplacers, etc. In addition, the US has reason to believe that “Pashtun cruelty is Uzbek kindness.” Scenario planners have dealt with the Taliban, Hezb-e Islami Gulbuddin (HIG), and Haqqani enough times to begin to understand and predict their reactions to US actions, but they might underestimate the ferocity, savagery, and tenacity of the Uzbeks.

In this example, the means by which staff uses ABM during wargaming may be different depending on the amount of time available to prepare. The study proposes 2 methodologies for using an agent-based capability, depending on available time; the first is an iterative multistep process whereby staff uses agent-based capabilities incrementally to assist in simulation of progressively in-depth and expanded questions and scenarios. A second methodology is to use an ensemble of cultural models during wargaming in order for a single simulation to help identify a breath of possible situations, interactions, and consequences.

In the first methodology, the incremental multistep version, the study identifies the steps involved and follows-up with a description of the need and value of each step based on the previous scenario; the objective is to use the agent-based tool throughout the entire course of action creation and wargaming analysis workflow, instead of treating it as a stand-alone tool. To begin, staff would use the agent-based tool to examine the culture and interaction tendencies of the local population in the designated area of operations. They would use the capability to identify a range of possibilities, ranging from action consequences to perceptions of the local population, if different actions and scenarios were chosen. For example, if a course of action had logistical consequences demonstrating a show of force, what might the perception of the local population be at the time of occurrence versus one week later? Alternatively, what might happen if there were an unexpected increase in the behavioral savagery in some elements of the population?

Second, once wargaming participants developed possible scenarios, use the agent-based capability to help identify what data could collected by the Army or another governmental organization to help validate whether predicted courses of actions were actually happening, or beginning to happen. For example, if a certain type of population-level interaction, such as women and children not observed in the streets, could indicate a future decision points, could these data be collected in a timely manner to produce actionable insights? Wargaming products, such as the synchronization matrix, could change if decision points identified an inflection point in circumstances.

Third, once staff identified a range of possible scenarios, use the agent-based capability to identify possible friction points and consequences that could negatively affect mission objective and success. Friction points could be due to physical constraints, such as traveling a route that historically has had more IED attacks, or social constraints, such as a decrease in the tenacity of the Uzbeks.

Fourth, once initial wargaming analysis is complete, use the agent-based capability to identify a range of alternate courses of action, constrained by initial conditions. In these cases, the agent-based capability could suggest alternatives, which wargaming participants did not identify because of either cognitive biases or context and pressure of the situation. Given appropriate computation power, the agent-based capability could model permutations of various culturally, tribal, and physiological conditions with the objective of identifying additional mission risk. The goal of these permutations is to identify both perceived and actual risks, from both parties' perspectives. Considerations of break-point thresholds, from the perspective of both friendly and adversarial forces, are an important consideration in this calculation.

Fifth, use the agent-based capability to determine possible, probable, and improbable consequences of each course of action. By independently caveating each course of action, the commander can make a more informed and rigorous choice.

A disadvantage of using the agent-based capability extensively during wargaming is a potential increase in needed time. During tactical situations, time will limit the ways such a capability may be used; however, the benefits of increased rigor and awareness of the cultural terrain are an appropriate contrast with the need to make situationally quick decisions (Spencer 2009). In the context of needing to make situationally quick decisions, there could be an alternate method for applying an agent-based capability. For example, perhaps it is more useful to use a single-step agent-based capability instead of a multistep capability. To model the cultural terrain in this case, the agent-based-capability could use an ensemble of cultural models to model a wide range of possible interactions with the local population. For example, individual agents with the model would have a mixture of cultural models, combining characteristics of the local people and geographically and socially surrounding cultures.

A single-step, agent-based capability could reduce the amount of time used by the tool while providing a degree of cultural and interaction rigor to the wargaming analysis. A disadvantage of this type of modeling is validation. This type of model is likely to be hard to verify; interactions, perceptions, biases, and actions may not have prior precedent to the simulated scenario. As such, this type of capability could provide value as long as staff interpreted output as representative caricatures of how the local population may react to proposed courses of actions.

3.7.2 Appropriate Tactical Level for Agent-Based Wargaming

Finally, the study considers the tactical level that is appropriate for an agent-based capability. Tactical planning occurs in Army divisions, brigades, and battalions. Based on our consideration, the authors believe the brigade is the lowest level that staff should use an agent-based capability during wargaming. There are several reasons for this conclusion (Barry and Koehler 2005).

First, the brigade is the lowest level of command that can operate independently as part of a JTF. It is the lowest level of command that integrates several intelligence military occupational specialties, such as all-source, imagery, human intelligence, and signals intelligence analysts. Comparatively, battalions and lower tactical levels of command do not include these capabilities. Battalions are not capable of operating independently and rely heavily on BCTs for guidance and intelligence support. Finally, BCTs have just as much intelligence capability as a division and the primary different between staff assigned to division and BCTs is rank and experience.

Second, the BCT is a modular organization that provides the land component or JTF commander with close-combat capabilities across the full spectrum of conflict (Greer 2013). BCTs are the Army's tactical-combat power-building blocks for maneuver, and they are the smallest combined-arms units that can be committed independently. Now and in the future, it is likely a single BCT from any of 10 active divisions will deploy as part of a JTF; in the future, the authors believe it is more likely for a BCT to be deployed than an entire division.

Third, when higher headquarters alerts a BCT for deployment or assignment of a new mission, its parent division, or JTF staff, is doctrinally responsible for providing an Analysis of the Operational Environment (HQ–DA FM 3-90.6 2009). However, this analysis is in the context of the operational variables and subvariables (e.g., PMESII-PT). The higher headquarters Analysis of the Operational Environment may consider aspects of the environment that are too broad for the tactical mission tasks of BCT.

According to Army doctrine, the BCT commander and his staff are responsible for refining this operational information and variables to its tactical relevance. With limited time and analytic capacity, BCT commander focuses his staff on those mission and operational sub variables that are mission-relevant. An agent-based capability could help staff identify which mission and operational variables will be mission-relevant in the end. Incorporating the operational variables into the mission analysis would enhance the BCT command and staff's early understanding of the human aspects of the situation; variables such as language, culture, history, grievances, education, beliefs, and so forth that traditional mission analysis might otherwise not fully consider.

In a hypothetical contingency situation, the division would have approximately one week to complete its MDMP, starting from mission receipt and ending with production of operations orders and supporting annexes. The next smaller command, the brigade, will have approximately two-thirds of that time. The brigade would have approximately 4 1/2 days to complete its own MDMP. The same time ratio applies to the battalion; it would have two-thirds of the brigade's time, assuming staffs honor the long-standing "one-third–two-thirds" practice, where planning at successive levels of command happen in parallel, and higher-level headquarters give their subordinate staffs as much time as possible.

Depending on the particular situation, the amount of time used for each step of the MDMP varies. In general, staff is not designing a campaign at tactical levels; they are nesting and synchronizing tactical courses of action in their area of operations. However, the objective is to quantify the amount of time available for wargaming and thus identify the limiting amount of time for using an agent-based modeling capability. Generally, course of action development will consume the most time and wargaming, the next largest amount. As such, the authors estimate the average amount of time used by each step as

- Step 1: Receive the Mission—5%,
- Step 2: Analyze the Mission/Frame the Problem—10%,
- Step 3: COA Development—40%,

- Step 4: COA Analysis/Wargaming—20%,
- Step 5: COA Comparison—10%,
- Step 6: COA Approval—5%, and
- Step 7: Orders Production—10%.

Therefore, given these estimates in this particular scenario, a division would have approximately 1 1/2 days to wargame all identified courses of actions, a brigade would have around 1 day, and a battalion would have a little over half a day. This assumes staff is working 24 h a day, once the contingency situation occurs and has received their respective higher-level headquarters' orders. The authors assess one day, or use at the brigade, is likely the minimum amount of time a user would need for appropriate use.

3.8 Summary

In this section, the report discusses ways an agent-based capability could improve the rigor of tactical Army wargaming. The variety and breath of tactical Army missions exhibit different cultural, social, and behavioral variables that cause emergent situations to occur. These emergent phenomena are the result of interactions between actors and their environment. The study identified several structured analytical processes that traditionally help improve rigor of analysis and demonstrated an agent-based model can embody the objectives that each process emphasizes. Then, the study identified how ABM could improve the rigor of tactical wargaming. The 8 metrics of rigor help identify areas where ABM has potential to improve rigor of Army wargaming practice. Finally, the study identifies how ABM could be applied to tactical wargaming, where constraints such as limited time and ease of use are essential for operators in the field.

4. Modeling Human–Computer Decision-Making

This section details the evolution of modeling the human-computing decision-making process in 3 subsections: Artificial Intelligence, Decision-Making, and Computational Social Science.

Since the 1950s, research in the field of artificial intelligence has illustrated the difficulties of computationally representing and modeling the human decision-making process. Numerous techniques have been proposed, researched, developed, and tested throughout the years. The first subsection details the evolution of artificial intelligence and its application to the tactical environment.

The second subsection surveys both the notion of decision-making and several decision-making frameworks and discusses how they could assist with individualized human decision-making. While decision-making is traditionally considered a cognitive human process, computational techniques and frameworks are beginning to demonstrate the value of semiautomated decision-making. The study therefore also identifies how semiautomated capabilities could potentially interact with and augment human decision-making.

The final subsection introduces the concept of computational social science, which is a combination of traditional social science and computational processing. Highlighted in this section is a computational technique known as agent-based modeling (ABM), which can model and realize characterizations of interactions within an environment over a simulated period. However, because agent-based models can be difficult to conceptualize and create, the authors identify research that proposes using design processes to create models simulating interactions. This section of the study concludes with a survey of the limitations and challenges of ABM.

4.1 Artificial Intelligence

Artificial intelligence is a branch of computer science dealing with simulation of intelligent behavior in computers (Merriam-Webster 2016). In 1955, McCarthy et al. proposed that artificial intelligence could embody a specification of learning and intelligence such that a machine could replicate it (McCarthy et al. 1955; Langley 2015). Since then, artificial-intelligence research has evolved to consist of a multitude of goals and algorithms. Moreover, its application has been involved in many interdisciplinary fields of study.

However, since the original artificial-intelligence proposal, the criterion of success has been ambiguous. As a proxy, researchers have identified and used tests to identify whether developed capabilities actually realize an artificial-intelligence capability. Alan Turing was one of the first people who proposed such a test, which involved 3 players: a questioner and 2 answering players (Turing 1950). The artificial-intelligence capability would pass the test if the questioner could not identify which of the 2 answering players was a computer. Turing suggested that if a computer could pass this test, then it would be a thinking agent.

Since then, others have suggested variations to Turing's original test. Edward Feigenbaum suggested that computers are not human brains; instead, artificial intelligence should be evaluated by its capabilities. If both a human and an artificial intelligence implementation could perform the same acts, then if one agent was considered intelligent, the other should be also be considered intelligent (Laufer 2013). Feigenbaum's test essentially removed Turing's requirement of casual conversation, replacing it with the requirement that a computer could solve problems that a human expert could solve (Smith et al. 2006).

Similarly, Nils Nilsson suggested an alternative test that evaluated artificial intelligence by means of an "employment test". Similar to the expert system proposed by Feigenbaum, the employment test further specified evaluation of artificial-intelligence capabilities in terms of jobs and tasks ordinarily performed by humans (Nilsson 2005). As such, Nilsson's suggestion helped to transfer the success criterion from an abstract notion to actual tests. He also summarized the broad artificial-intelligence field into notional categories of research, which are 1) Sensory–Motor System, 2) Hierarchies of Perception, Representation, and Action, 3) Predicting and Planning, 4) Learning, 5) Reasoning and Representation, and 6) Language. Figure 14 illustrates each of these categories:

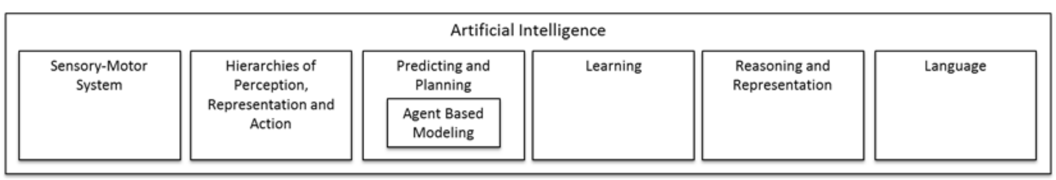

Fig. 14 Nilsson's categorizations of the field of artificial intelligence. The figure also identifies ABM as falling within the scope of Predicting and Planning.

The following sections briefly describe and summarize the nature of artificial intelligence research in each of Nilsson's proposed categories.

4.1.1 Sensory–Motor System

The sensory–motor system is the set of physical capabilities associated with robotics and includes domains such as visual, tactile, audio, and haptic. Example tasks include manipulating physical objects and conceptual concepts, including navigation, mapping, and path planning. Navigation includes localization subproblems, such as knowing where the agent is located and knowing where other items are located with respect to its current location. Mapping is the ability to learn and create an internal spatial map. Path planning is the routing capability that identifies motion paths from source to destination locations (Gigras and Gupta 2012). Learned conceptual knowledge is specific to each agent, who may choose to communicate its findings.

4.1.2 Hierarchies of Perception, Representation, and Action

Hierarchies of perception, representation, and action represent respectively knowledge abstraction, the process of annotating sensed information, and the resulting actions that an agent may take.

Perception is the ability to interpret input, such as data from sensors, which include modalities of speech, facial, and object recognition. Robust perception has been a challenge for researchers ever since the inception of artificial intelligence. At first, researchers tried to develop detailed and complete representations, independent of other parts of the system. However, recent studies have emphasized evaluation of perceived data within the holistic system to realize the greatest improvement; many times, perception is only a single aspect of the overall problem and solution (Fitzpatrick 2003).

Representation is commonly associated with a knowledge map consisting of objects, properties, and categories, and their interrelations. Several representations of perceptions exist, including data structures called frames or semantic networks, among others. Representation may also store temporal representations of situations and events, such as cause and effect relationships. The relationship between perception and representation is primarily complementary, where representation embodies the interpreted storage of observations and assertions. Existing knowledge bases of context- and domain-specific information can assist with annotation of observations (Rajeswari and Prasad 2012). Metadata, or data about data, are generally included in the knowledge-representation category.

Actions may be the result of preconceived or reactive analysis, depending on the situation and context, but both perception and action components are part of an integrated process. For example, several cognitive architectures, such as SOAR (state, operator and result) and HiTEC, have demonstrated the utility of interconnected processes (Wray and Jones 2004; Haazebroek et al. 2011). With either of these architectures, preconceived actions are often the result of a balanced analysis, where logic routines have considered the benefits and risks before action. However, these architectures have also modelled reactive modes, where a pseudosubconscious methodology improves performance in time-sensitive applications but does not consider the implications of the actions.

4.1.3 Predicting and Planning

Predicting and planning capabilities identify a range of possible future states that can result from hypothetical actions. From a psychological perspective, predictions form the basis of making plans, specifically to achieve goals. Historically, agents have assumed planned actions would result in the intended consequences. However, these assumptions have evolved. Researchers have begun to consider multiagent problems where actors need to observe whether predicted circumstances continue to match expectations. Specifically, in cases where multiple actors interact, subtle aspects of social intelligence and creativity can influence outcomes.

Emergent behavior is the property and consequence of social systems; the interactive nature of groups tends to cause unexpected outcomes. Agent-based models are a computational technique that can identify the range of likely possible actions (Gilbert 2007). Moreover, the technique can compute a range of possible future outcomes (Jennings et al. 1998). Agent-based models are designed by using state diagrams that represent transitions between choices. Each transition is associated with a distribution, which represents the probabilistic choice of making decisions. It is plausible that an artificial-intelligence capability could use an agent-based model to assist with planning, to preemptively identify emergent or unexpected consequences and identify risks to overall objectives. Based on model results, the artificial-intelligence capability could adjust its planned course of action appropriately.

4.1.4 Learning

Artificial learning is the ability of algorithms to improve through imitation, experience, practice, and education. Two classes of algorithms widely referred to as “supervised” and “unsupervised” embody these capabilities; “semi-supervised” algorithms are a hybrid, a mixture of the 2. Supervised algorithms tend to include techniques based on classification, regression, or statistics, whereas unsupervised algorithms attempt to infer an unknown structure from data. Regardless of the technique used, at some point learned information needs to be represented in the aforementioned category—perception, representation, and action hierarchies—for subsequent use.

Supervised learning is a technique where an algorithm evaluates provided data and the user observes the difference between the expected and computed answers (Rojas 1996; Kotsiantis 2007). A feedback process updates algorithmic rules and weights depending on the magnitude of the difference. The nature of the feedback process is either corrective or supportive. Classification algorithms are a form of inductive learning, where labeled instances create and train the model (Kotsiantis 2007). For example, a decision-tree classification model is the result of forming structured, hierarchical rule sets. Once complete, the decision-tree model classifies other similar data into its learned categories. Regression techniques can be as simple as a linear model formed by minimizing the least squares error. A Bayesian network is a statistical technique in which the probability of classification is dependent on conditional interdependencies of features evaluated (Diez and Druzdzel 2003; Mooney 2010).

In comparison, several other types of algorithms such as reinforcement, clustering, and game-theory-based learning are used for unsupervised learning (Bkassiny, Li, and Jayaweera 2012). Reinforcement learning is the result of the way algorithms interact with the environment and adjust their own internal weights to improve the reproduction of the desired output (Rojas 1996; Ghahramani 2004). For example, neural networks exemplify networks of highly interconnected and weighted nodes, which produce an arbitrary output from a given set of inputs (Hajek 2005). Clustering is a grouping process where subsets somehow reflect the underlying structure of the data. However, groups are an artifact of comparison criteria used (Moutari 2013). For example, k-means clustering is a method that produces k-number of clusters. Game-theory-based learning is a generalized form of reinforcement learning. Its primary difference compared to other learning algorithms is that the environment is not static. Other agents can sense and interact with the environment. The goal of this algorithm is to maximize rewards, both short and long term. There has been a significant amount of work done in game theory for simple systems, but the dynamic case of multiple adaptive machines remains an area of active research.

4.1.5 Reasoning and Representation

Reasoning and Representation is an essential component of artificial intelligence. Reasoning is the process of determining information not stated explicitly. Traditional forms of logical reasoning include deduction, induction, and abduction. Deduction is the inference from the general to the particular. Induction represents the inference of the probable from the particular to the general. Abduction is the inference from the result to a rule and provides a plausible explanation of observations. As demonstrated by Oliver Ray, using these reasoning types together can create a powerful artificial-intelligence capability (Ray 2005).

Additional approaches exist for dealing with uncertain or incomplete information. Approaches include Bayesian networks, fuzzy logic, and Dempster–Shafer theory. Bayesian networks are directed acyclic graphs that indicate a probabilistic causal structure. Fuzzy logic characterizes relationships between real-world entities and specific concepts without explaining the nature of the relationship (Freksa 1994). Dempster–Shafer theory is a method that combines evidence and recognizes that each fact has a degree of support ranging from full support to no support (Zadeh 1986).

In addition to these reasoning types, several forms of knowledge representation exist, such as schemas, predicates, frames, scripts, situation models, and semantic networks (Gow 2003; Crowley 2012). Each type of representation has its utility and advantages. Schemas are the oldest form of representing information and developed to demonstrate that not all truth was an empirical observation. Predicates use relationships to express the structure of entities in structured knowledge form. Frames provide a contextual and structured representation for focusing on visual interpretation; they use slots (placeholders for entities) and methods (corresponding logic to search for entities). Scripts are another data structure used to represent sequences of events. Cognitive psychology uses situational models to express mental models of human comprehension. Finally, semantic networks are directed networks of semantic relations between concepts. For example, an ontology is a semantic network that uses known types of objects, relations, and concepts.

4.1.6 Language

Language is a component of artificial intelligence used to communicate among other agents, including both human and other artificial agents. For example, natural language processing gives machines the ability to read and understand human language. Alternatively, machine-to-machine communication uses interfaces to convey syntactic and semantic information.

Nilsson's categories as described previously thus represent the major categories of study within the field of artificial intelligence. His "employment test" variant on the Turing test, however, is by no means the last word on the subject. Negroponte suggests yet another variation of the Turing test, in which he identifies that the value of a thinking computer is in its ability to work together with a human, rather than just passing a capability test (Smith et al. 2006). Similar to Nilsson's test, Negroponte's test justifies artificial-intelligence capabilities by their results. However, this test reintroduces the human element, evaluating how human-cognitive aspects affect whether artificial support actually improves human performance. It is this aspect of modeling human cognition that comprises the subject of the next section.

4.2 Decision-Making

Decision-making is a process that chooses a preferred option or a course of actions from among a set of alternatives based on given criteria or strategies (Wang and Ruhe 2007). Yingxu Wang and Guenther Ruhe have identified 2 types of human cognitive-decision theories: descriptive and normative. Experimental observation and studies form the basis of descriptive theories, whereas rational decision-making and behavior comprise normative theories. Additionally, Wang and Ruhe identified 4 types of cognitive strategies used during decision-making: intuitive, empirical, heuristic, and rational. When making decisions, human cognitive processes generally use one of the first 2 strategies. Existing rational models do not explain these intuitive and empirical types of decisions.

However, when a person is making decisions, heuristic and rational techniques are generally used. Heuristics include decisions based upon guiding criteria such as principles, ethics, rules of thumb, availability of information, and other anchoring biases. In comparison, rational decision-making is the result of either static or dynamic decisions. Static decisions are the result of structural or deductive analyses of the situation, whereas dynamic decisions involve an estimate of the dynamics of multiagent interactions.

Wang and Ruhe identify a generic decision-making tree, which humans use to select their decision-making methodology (Fig. 15). Their work concludes that while humans may decide to make rational decisions, the selected methodology changes depending on the perspective of the situation specific to the time of the selection. As might be expected, employing different methodologies often results in different conclusions and results. From a tactical wargaming perspective, changing methodologies implies variability in the many decisions and conclusions identified during wargaming, simply because participants may change which decision-making strategies they use. This variability translates into reduced wargaming rigor.

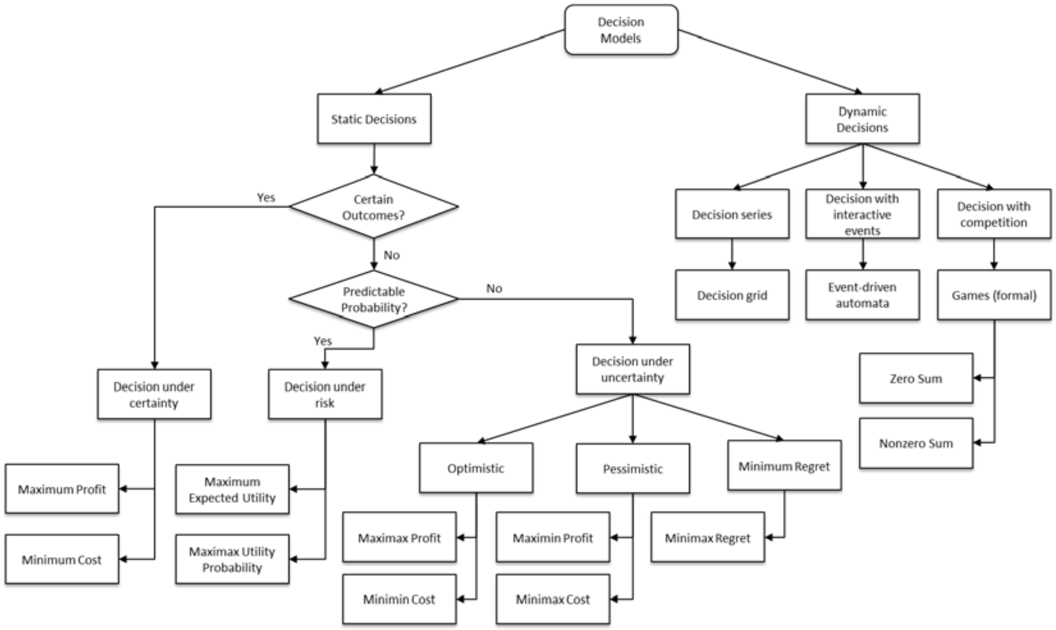

Fig. 15 Wang and Ruhe's cognitive framework of decision and rational decision-making strategies. A decision tree illustrates paths of selected strategies, which depend on the individual's perspective of the situation.

With the advent of artificial-intelligence research, cognitive strategies have become augmented with a variety of computationally defined decision-making strategies. Many of these techniques have been derived from research in the Operations Research field, and they often search for optimal methods of making decisions while using multiple attributes to contribute to the decision-making process. Several examples of these computational techniques include multiattribute utility theory, analytic hierarchy process, outranking methods, and evidential reasoning, among others.

The decision-making process itself uses the selected methodology, and both the decision-maker and all the stakeholders are ideally involved in the decision-making process, to reduce disagreement about the problem's definition, requirements, goals, and criteria (Harris 2012). Janos Fulop summarizes the generic decision-making process using the following steps (Fulop 2005):

1. Define the Problem: root causes, limiting assumptions, system and organizational boundaries and interfaces, and stakeholder issues

2. Determine Requirements: conditions that any acceptable solution must meet

3. Establish Goals: broad statements of intent and desirable values

4. Identify Alternatives: different approaches for changing the initial conditions to the desired conditions
5. Identify Criteria: objective measures of how well each alternative achieves stated goals and requirements
6. Select a Decision-making Methodology: the method used to solve the decision problem; a strategy is often selected using the aforementioned strategy decision tree
7. Evaluate Alternatives Against Criteria: evaluate alternatives using criteria and associated weighting and rank alternatives according to value
8. Validate Solutions Against Problem Statement: ensure selected solution adequately meets requirements and goals; if the best solution is not adequate, repeat the process of identifying alternatives and criteria until an appropriate solution is found

4.2.1 Decision-Making Frameworks

Negroponte's variation of the Turing test mentioned previously includes not only the technological artificial-intelligence capability but also its interface with human decision-making processes. Depending on the nature of the artificial-intelligence capability, either a single person or a group of stakeholders may interact with the machine. Several decision-making frameworks have begun to experimentally discover the nature of this human–technology interaction. This section reviews several of these frameworks and their associated interactions.

4.2.1.1 Data Fusion

Data fusion is one framework used to represent capabilities intended to assist human decision-making abilities. The term "data fusion" grew out of work within the defense community after the Joint Directors of Laboratories' (JDL) Data Fusion Group published a Data Fusion model. Researchers often realize data-fusion capabilities by integrating multiple data sources and knowledge to estimate or predict the state of some aspect of the universe (Steinberg et al. 1999).

The original version of the JDL model identified 4 levels of fusion: (Level 1) Object Assessment, (Level 2) Situation Assessment, (Level 3) Impact Assessment, and (Level 4) Process Refinement. Object Assessment is the estimation and prediction of entity states based on observation, which tracks association, continuous state estimation, and discrete state estimation. Situation Assessment is the estimate and prediction of relations among entities and may include force structure, cross-force relations, communications, perceptual influences, and physical context. Impact

Assessment is the prediction and estimate of actions and consequences resulting from interactions between actors. Process Refinement is the adjustments or changes made to observations and processing to support processing objectives.

However, subsequent revisions of the JDL Data Fusion Model included additional categories: (Level 0) Sub-Object Data Assessment and (Level 5) User Refinement or Cognitive Refinement. Sub-Object Data Assessment is the estimate and prediction of the signal or other observable states necessary for data characterization and association. User Refinement is the presentation of information to the user so they can specify changes to the system. Most recently, (Level 6) Mission Management has been added into the Data Fusion model and defined as the cost, location, and coordination of sensors and platforms (Blasch 2006). The notional JDL model is shown in Fig. 16.

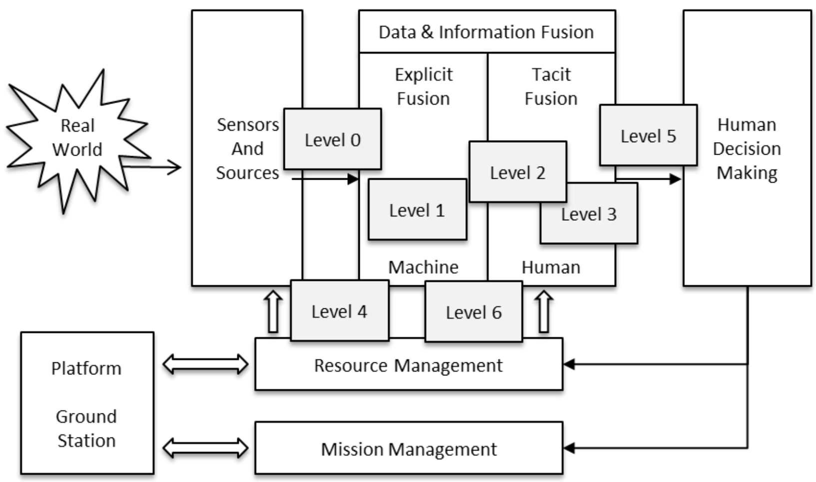

Fig. 16 A notional JDL Data Fusion Model is composed of 6 levels, which represent abstract notions of data representation and interpretation. Levels 4–6 have recently identified interaction with external entities, dealing with issues of resource management, human interaction, and multiagent coordination.

In addition to each of the 6 fusion levels, the Data Fusion Model identifies the notional concept of distinct processing steps taking place within each data-fusion level. Figure 17 illustrates each of these steps, which include common referencing, data association, and state estimation and prediction.

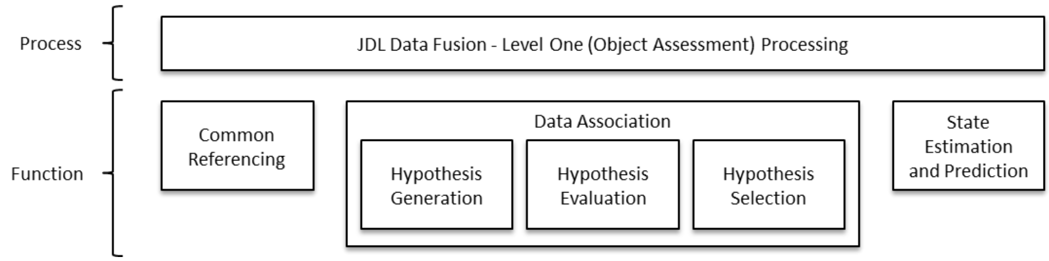

Fig. 17 An illustration of the functions that occur at each level and node within each JDL Data Fusion level.*

The first function is common referencing—also known as data alignment—and it includes data-preparation processes. Data transformations could be simple or complex. A simple example might include a coordinate transformation, whereas a difficult example might include converting uncertainty representation (i.e., probability and possibility) into a frame.

The second function is data association, the purpose of which is to assign data to the appropriate fusion processes. Three subfunctions comprise data association: hypothesis generation, hypothesis evaluation, and hypothesis selection. Hypothesis generation is the enumeration of observation sources within the context of the problem domain. Hypothesis evaluation is the computation of how close the data relate to different hypotheses. Hypothesis selection is an assignment problem, sometimes known as the combinatory optimization problem in Operations Research.

The third function is state estimation and prediction, the purpose of which is to resolve data associated in the prior step and place them into context within the fusion level. Both attributive and relational states may exist. Furthermore, aspects of each state estimation may be discrete, continuous, or both. For example, the result of a Data Fusion, Level 2 state estimation may be the location of object, the annotated type of object, or an identified spatial error bounds.

4.2.1.2 Decision-Making Frameworks—Observe, Orient, Decide, and Act (OODA) Loop

The OODA loop, as proposed by John Boyd, describes another decision-making framework. As commonly referred to, the first 2 steps identify processes that perceive, interpret, and project entity statuses. These statuses allow a user to have situational awareness and make decisions during the Decide and Act steps. However, Boyd best describes the OODA loop as “observe, orient, decide, and act

*Figure is adapted from “Lesson 2: The JDL Model” (Hall 2008) and “COIC Information Fusion Operations and Capabilities: An Initial Assessment” (Del Vecchio et al. 2010).

more inconspicuously, more quickly, and with more irregularity" (Boyd 1986). Figure 18 shows Boyd's diagrammed decision-making model using the following illustration (Boyd 1996; Boyd et al. 2010):

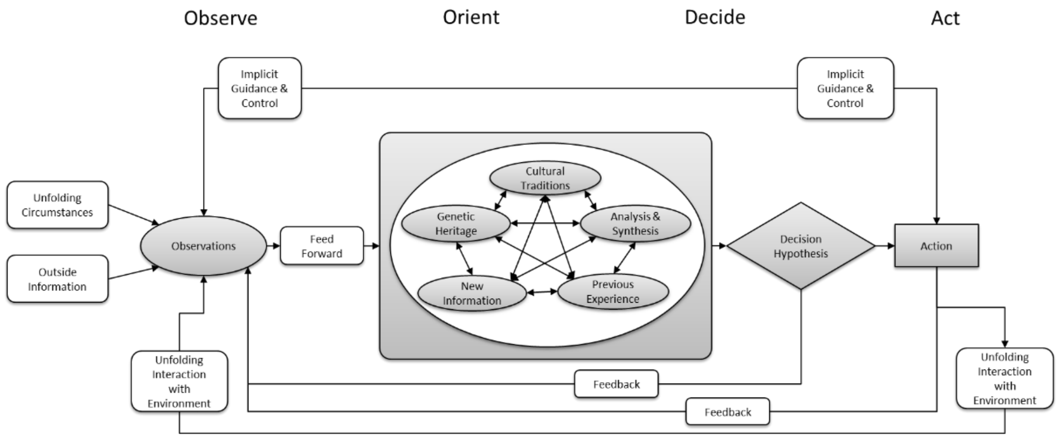

Fig. 18 Boyd's OODA loop used to illustrate the way one can create opportunities to act in ways that opponents will see as irregular and disorienting.

Central to the OODA loop is the identification of 5 elements: genetic heritage, cultural traditions, previous experience, analysis and synthesis, and new information. Boyd states the environment and experience conditions the repertoire of opponent psychophysical skills. However, without analysis across a breadth of information, insights to develop new actions cannot be created. Boyd suggests that the diagram lines identifying Implicit Guidance and Control should be used to guide standard activities (Richards 2012). The term "implicit" indicates actions, which are executed out of habit or a common understanding of the objective. The lower line, identified as Feedback, indicates experimental and thoughtful adjustments to existing repertoires. The interactive results exhibited by the environment provide guidance for iterative adjustments.

Dr Mica Endsley proposed a similar form of a decision-making framework from an information-system perspective (Endsley 1995). Her version kept the last 2 steps of the OODA loop (Decide and Act) but adjusted situational awareness to specify 3 steps: 1) Perception of Elements in Current Situation, 2) Comprehension of Current Situation, and 3) Projection of Future Status. The model, shown in Fig. 19, also identified task and system factors (the upper region of the diagram) and individual cognitive factors (the lower region of the diagram) (Paradis et al. 1999).

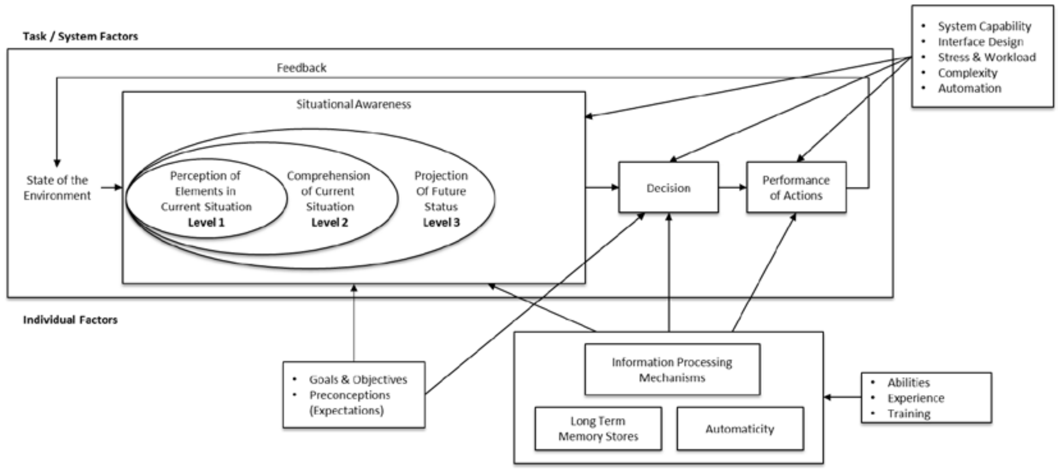

Fig. 19 Endsley's model of situational awareness for dynamic decision-making. While similar to Boyd's OODA loop, it explicitly identifies projections of future status and identified individual factors influencing the implementation of actions.

4.2.2 Human and Artificial Intelligence Interaction

The Data Fusion framework appears to correlate to Nilsson's artificial-intelligence category of Hierarchies of Perception, Representation, and Action. Data Fusion focuses on sensed modalities and relative contextual knowledge to identify states of situations, as best as possible. Once the data-fusion system has identified entities, the framework puts emphasis on identifying context around those entities. Subsequent JDL Data Fusion Model revisions and the addition of a Level 5 User Refinement to the JDL Data Fusion Model have indicated the need for artificial-intelligence capabilities to work cooperatively with humans.

Comparatively, both Boyd's and Endsley's models identify cognitive aspects in their relation to the broader situational context. As such, original versions of these 2 models correlate with Negroponte's artificial-intelligence test, where he locates the value of artificial intelligence in the success of the capability working together with humans.

However, the interaction of an artificial-intelligence capability with a human is not trivial (Dillon 1998; Dietvorst et al. 2014; Pfautz et al. 2015). As discussed previously, humans use a variety of strategies for decision-making. Moreover, Schneiderman (1992) recognized situations where humans and machines have different strengths and weaknesses in performing tasks. Algorithms tend to exhibit strengths in deductive capabilities, whereas humans tend to have strong inductive-reasoning skills. At the same time, current algorithmic capabilities still have relatively weak induction capabilities, and humans tend to have difficulty cognitively evaluating multiple hypotheses at the same time. A human working with an artificial-intelligence capability could benefit the decision-making outcome in a variety of ways. For example, humans identify hypotheses better than a computer, but a computer may validate those hypotheses better. As a disadvantage, human interaction with a computer may increase the number of problems requiring attention (Paradis et al. 1999).

A paper by Breton, Rousseau, and Price suggests that a 3-part model could be useful in identifying requirements appropriate for balancing algorithmic and human capabilities (Breton et al. 2002). In the paper, the authors identify the need for Human Factors cognitive engineering, specific to each application. This identifies system-level engineering requirements that support and improve the effectiveness of interaction. The 3-part model includes the particular task, technology, and human. The model recognizes that either deficiencies caused by the machine or the human will cause friction within the whole system. For example, an algorithm deficiency will cause the human to do extra work to compensate. A tradeoff spectrum results, balancing requirements between the artificial-intelligence capability and the human. Placement within the spectrum will affect the overall human–machine synergy and effectiveness.

In 1999, Endsley developed an automation framework to identify the nature of automated capabilities supporting human decision-making. A 5-level framework identifies the cognitive level required by an operator. The first level is human manual control without any automated assistance. The second level results in a decision support system with which users would interact and from which they would receive recommendations. The third level is a consensual system, where the artificial-intelligence system would implement actions, pending approval of a user. The fourth level is an automated system monitored by a user, in which the user could veto actions. The fifth level is a fully automated system without any user interaction.

Similarly, the National Highway Traffic Safety Administration recognized and identified a method to evaluate how well human and artificial-intelligence capabilities are combined (National Highway Traffic Safety Administration 2013; Zheng et al. 2013; Li et al. 2014). They identified 5 levels of automated interaction, similar to those originally proposed by Endsley, in which different rules or regulations would apply. Levels ranged from no automation through full automation and were identified as follows:

- Level 0: No automation,
- Level 1: Function-specific automation,
- Level 2: Combined function automation,
- Level 3: Limited self-driving automation, and
- Level 4: Full self-driving automation.

At Level 0, the driver is in complete control and is solely responsible for monitoring the roadway. At Level 1, automation involves a specific control function, such as electronic stability control or a crash-imminent situation where dynamic brake support is used. At Level 2, at least 2 control functions work together, but the system can relinquish control without warning. At Level 3, drivers may cede full control under certain traffic or environmental conditions. At Level 4, the vehicle can perform all functions for an entire trip.

Most comprehensively Kaber and Endsley (2003) developed a 10-level taxonomy that better described the spectrum of human–machine interaction. They also identified the responsible party and associated roles for monitoring, generating, selecting, and implementing functionalities. Tables 2 and 3, respectively, identify and summarize each level of automation and the roles assigned to either the human or the algorithmic capability.

Table 2 Endsley and Kaber's levels of automation, expanding upon Endsley's original 5 levels of automation

Level of automation	Description
(1) Manual control	Human performs all tasks (e.g., monitoring, generating options, decision-making, implementation)
(2) Action support	Human generates and designates action, system assists by performing action
(3) Batch processing	Human generates and selects tasks, the system executes batches of tasks
(4) Shared control	Human and system generate options, but the human selects tasks; the human and system execute tasks
(5) Decision support	System and human generate options, but the human selects tasks; system executes tasks
(6) Blended decision-making	System generates and selects options, the human approves; system executes tasks
(7) Rigid system	System allows human to see and select limited options; system executes tasks
(8) Automated decision-making	System generates options; human may suggest options; system selects best option and executes tasks
(9) Supervisory control	System generates options, selects best option, and executes tasks; human monitors system
(10) Full automation	System generates options, selects best option, and executes tasks; human cannot intervene

Table 3 Endsley and Kaber's taxonomy for human and algorithmic systems operating in dynamic, multitask scenarios

Level of automation	Monitoring role	Generating role	Selecting role	Implementing role
(1) Manual control	Human	Human	Human	Human
(2) Action support	Human/system	Human	Human	Human/system
(3) Batch processing	Human/system	Human	Human	System
(4) Shared control	Human/system	Human/system	Human	Human/system
(5) Decision support	Human/system	Human/system	Human	System
(6) Blended decision-making	Human/system	Human/system	Human/system	System
(7) Rigid system	Human/system	System	Human	System
(8) Automated decision-making	Human/system	Human/System	System	System
(9) Supervisory control	Human/system	System	System	System
(10) Full automation	System	System	System	System

The Data Fusion community, while primarily focused on the technological capability, has proposed several methodologies for describing human–machine interaction. These include human-in-the-loop, human-on-the-loop, and human-inside-the-loop (Sudit 2015). Figure 20 illustrates the relative position of the human within each said interaction. In terms of Endsley's levels of automation (LOAs), human-in-the-loop implementations are comparable to LOAs 2–5, human-on-the-loop implementations are comparable to LOA 6, and human-inside-the-loop implementations are comparable to LOA 8.

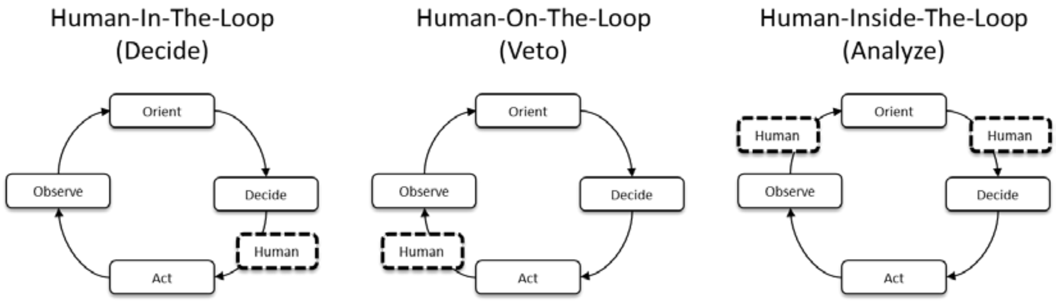

Fig. 20 Illustration of each of the 3 proposed human–machine interaction concepts from a Data Fusion perspective. In each variation, the point at which the human influences the interaction is highlighted.

In human-in-the-loop, the human acts as a “gate” between the Decide and Act phases of the OODA loop. For example, “Advanced Chess” is a form of chess that embodies this type of interaction (Kasparov 2010). This type of chess game allows algorithmic capabilities to assist a human player but requires the human to make the final decisions (Drogoul 2007). However, because the computer is assisting the human, the human may choose moves that are normally beyond his or her own abilities. Interestingly, in some experimental observations cooperation enables the human to achieve a performance rating higher than the rating of either the player or the standalone algorithmic capability.

Human-on-the-loop switches the roles of the algorithm and the machine. The human interacts between the Act and Observe phases of the OODA loop and operates in a supervisory role. In this role, the human may veto algorithmic decisions and plans. The artificial intelligence algorithm gains a supervised level of autonomy while operating within goals specified by the human. For example, Hawthorne and Scheidt suggested using swarm behavior algorithms, within unmanned vehicles, that implement the mechanics of individual or combined tasks while constraining overall action within the human-specified goals (Hawthorne and Scheidt 2005).

Human-inside-the-loop is the third form of interaction design and proposes integrating the capabilities of the machine and the human. The human takes on the role of an intelligence and cognitive analyst and uses their own knowledge and reasoning to prioritize and weight automated decisions. The human assigns weights at 2 points, between Observe and Orient and between Orient and Decide. In this type of system, maintaining a balance between objectives is necessary. For example, objectives might include minimizing risks, minimizing deviations from expected outcomes and costs, and maximizing reliability (Ganapathy 2006).

The methods and frameworks described are important representations of semiautomated decision-making. However, a majority of these techniques refer to individualized entities. The next section investigates the difference between individual decision-making and collective decision-making through computational social science, specifically targeting the emergent phenomena that result from the interactive nature of individual decision-makers.

4.3 Computational Social Science

Computational social science is an emerging field of study that leverages the modern capacity to collect and analyze data with unprecedented breadth, depth, and scale (Lazer et al. 2009). Similar to complex adaptive system modeling, technological integration measures social interactions and has enabled research toward a quantitative understanding of complex social systems (Conte et al. 2012). As such, computational social science is the intersection and mixing of social science, computer science, and statistics.

Computational social-science researchers seek to study and identify attributes of self-organization, emergence of collective phenomena and behaviors, and spontaneous order; such research is thus of great use to increase our understanding of collective decision-making (Fromm 2006). Emergence is the property that results from the interactions of agents within a system. In computational social science, there are 3 levels of emergence: the social behavioral level (microlevel), the social aggregate level (macrolevel), and the institutional level.

4.3.1 Emergence at the Social Behavioral Level

At the microlevel, interactions of heterogeneous agents identify social complexity. Heterogeneous agents are composed of multiple classes of virtual agents that emulate people, and their decisions and actions produce the interactive effect (Axtell 2011). Some amount of rationality limits the bounds of decisions each agent class makes. Researchers model interactions computationally, often using game theoretic principles or heuristic ABM techniques (Singer et al. 2008). Other evolutionary methods, such as genetic algorithms and various forms of game theory, are alternative techniques modelers can use (Stanford Encyclopedia of Philosophy 2009).

One microlevel area of computational social-science research is modeling individual behavior. While in some cases, this topic is technically possible because many personal actions can be observed and stored (Aviv et al. 2010); ethics and privacy concerns limit such work (Eloranta 2015). For example, how friends influence each other's purchasing behavior is an interesting question to social scientists. The same question also interests marketers and policymakers, each for their own reasons. Other questions of interest include inferring intent from search data and inferring relationships from network data (Watts 2013). Additionally, questions of individualistic social behaviors such as altruism and cooperation are concerned with whether cooperative behavior emerges and whether it can improve performance of collective tasks (Conte et al. 2012). Individual and agentic cognitive modeling research is another area of interest in modeling social behavior (Bandura 2002).

4.3.2 Emergence at the Social Aggregate Level

At the macrolevel, social systems are multilevel. Many layers of reproducible and heterogeneous systems may exist (Axtell 2006; Camus et al. 2013; Carley 2013; Makowsky and Smaldino 2014). However, the difficultly is that one cannot infer the properties of the microagents from results that emerge at the macrolevel (Cordi 2014). The same is true for macro results; microlevel specifications do not necessary indicate macrolevel results. However, one can characterize the macrosystem statistically but one will not know the exact outcome of the system, at a given point in time.

A macrolevel area of computational social-science research is identifying the way groups of individuals interact, such as modeling how a disease spreads among different populations and regions. In this example, the result tends to look like an S-curve, where the initial spread of the disease is slow, infection speeds up rapidly, and finally slows down until it dies out (Schelling 2011). Other social phenomena exhibit similar response-caricatures, as in the production and adoption of manufactured products. Other related research questions include how spontaneous groups form and when the emergence of coalitions begins (Conte et al. 2012).

4.3.3 Emergence at the Institutional Level

Social organization and the modern state exhibit an institutional form of emergence (Scheutz et al. 2005). Game theoretic rationality theory has provided a basis for modeling emerging conventions and social norms (Bueno de Mesquita 2010). Axtell has performed research in modeling the emergence of firms in a population of agents (Axtell 1999, 2014, 2016). Other related topics of research include modeling governance and modeling nationwide economies (Pike and Brown 2011; Richardson et al. 2015; Suslov et al. 2015).

4.3.4 Creating Computational Social-Science Models

The objective of computational social-science models may be either quantitative or qualitative, depending on how the modeler plans to use the results. Qualitative models may produce a caricature or reveal the nature of the actual observed data. Quantitative models statistically replicate nuances observed in the population. Axtell and Epstein address the breadth of these differences by proposing an evaluative framework to help communicate which type of model to use, and what its output specificity should be. The next part reviews this model in more depth (see Section 5). Both quantitative and qualitative objectives may be useful in modeling decision-making.

Another area of study within computational social science is the modeling of the mind, which includes beliefs, perceptions, desires, intentions, value, and processes. These types of models are applied representations of real-world populations and rely on cognitive science and social-psychology factors. Actors within these models make decisions with some degree of uncertainty. The transitions between different states are modeled stochastically, using rules with attached probability distributions.

One of the most applicable types of computational social science is a model of interactive behavior known as ABM.

4.3.5 Agent-Based Modeling

ABM is a technique used to implement computational social science theories. Modelers begin with the assumption that they can model aspects or attributes of arbitrarily intended behavior and its associated interactions (Macal and North 2006). They also assume that the involved social processes can be described, and they can create them from a combination of elemental components and interactions. In practice, modelers can emulate social phenomena replicating individualized decision-making processes, groups, organizations, and swarms of entities interacting together within their environment.

As discussed in Section 3, within this type of model each agent is a discrete and autonomous entity with its own goals and behaviors (Adra and McMinn 2010). Like people, agents are diverse and heterogeneous. As such, the nature of decision rules varies by the type of agent, based on, for example, the sophistication of the individual agent’s rules (Axtell, Andrews, and Small 2002). Moreover, the cognitive ability of agents varies. In simple cases, if-then-else rules may guide decisions, depending on conditions. In complicated behavior, if-then-else rules may have probability distributions attached to them, which cause the election of rules to exhibit stochastic properties. As this model is developed into the future, individual agents may eventually use cognitive decision-making models, such as those demonstrated by ACT-R (adaptive control of thought–rational; [Anderson et al. 2004]) or SOAR (Axtell 2015).* Future agents may also exhibit the ability to retain memory, which would allow agents to recall learned experience and use memories as input to their decision-making process (Kope et al. 2013; Ezhov and Terentyeva 2014). Future agents may also employ models of internal perceptions of the external world, causing agents to make decisions based on their perceptions of other actors and on the environment, rather than using strict comparisons and evaluations.

Modelers use relatively simple rules to create behaviors which, when instantiated within a population of agents, create the illusion of a globally organized flocking behavior. Such rules can successfully model a group of agents that exhibits apparent cohesion-, separation- or alignment-based rules but does not possess overall command and control facilities. In the case of flocking behavior, agent-embodied cohesion rules change the direction of individual agents toward the average position of viewable neighbors. Similarly, separation rules adjust an agent's position to avoid crowding, as perceived by localized neighboring agents. Finally, alignment rules adjust the direction of the agent toward the average heading of sensed neighbors. The aggregate result of these decentralized rules is the emergence of an organized group behavior without a central authority or controller.

In addition to agentic interactions and resulting emergent behaviors, agents also interact with the environment. In simple spatial cases, Euclidean 2- or 3-dimensional (2-D, 3-D) space is used. However, topologies that are more complicated may be used instead, such as grids, asymmetric or directional networks, and Geographical Information System (GIS)-based systems. Agents may use the environment as a "blackboard" communication tool. For example, a foraging ant uses the environment to place pheromones, which are subsequently detected and used by other ants to identify popularity of recently used routes. Thus, a group of ants with no central controller will eventually identify the shortest path solution between their nest and a food source.

Similar to other algorithmic capabilities, ABM excels at some applications but not as well in others. There are 4 conditions that indicate whether the application of agent-based modeling to a designated problem is appropriate: 1) natural representations of agents describe the problem; 2) the past is not a useful predictor of the future; 3) if the model needs to scale to an arbitrary number of agents; and 4) if the scenario needs to exhibit the possibility of unexpected or emergent phenomena (Macal and North 2006, 2008).

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*R. Axtell presentation at Computational Social Science Society of the Americas 2015 Conference

ABM exhibits the natural representations of agents when the following criteria are met:

- The modeler can identify and define discrete decisions and/or behaviors.
- Agents adapt and change behavior or exhibit objective-based behaviors.
- Agents have transient relationships, interactions, and group memberships.
- Agent behaviors incorporate spatial components into their behaviors and interactions.

The application of ABM illustrates a transition from traditionally deductive decomposition and composition of system components to the composition of individual entities that interact to produce a resultant phenomenon. As illustrated in Table 4, Dr Axtell details this progression well in his comparison of traditional modeling practices and its results with the newer computational social-science modeling field, its associated ABM, and its more expressive results (Axtell 2006b, 2011, 2015):

Table 4 Axtell's comparison of traditional modeling methods, techniques, and processes with newer, computational social-science techniques

Simple (20th century)	Complex (21st century)
Single decision-maker	Multiple agents
Scalar value function, first-order conditions, numerical solutions	Heterogeneous utilities, purposive behavior, agent models and simulation
Decision theory	Game theory
Mean field, averages	Networks, extremes
Schema, taxonomy	Ontology
Equilibrium, fixed-point theorems	Volatility, adaption, coevolution
Continuous, smooth mathematics	Discrete mathematics, computation
Command and control	Bottom-up emergence

4.3.6 Process for Implementing Agent-Based Models

To employ such agent-based models for decision-making processes, it is necessary to understand the theoretical process of creating these models, which requires a combination of 3 perspectives (Conte et al. 2012).

The first perspective required is to understand and create a model that emulates the necessary behavior (Bozkurt 2015). Once the model is working properly, it should characterize the nature of plausible results. Models provide insight into the representative processes and interactions of systems. A common use of models is to illustrate how systems work, serving as an example that explains a particular behavior (Schieritz and Grobler 2002). The model may be abstract or precise but should illustrate how states evolve within a given system. Moreover, it is common for the logic of the model to remain constant while properties change.

The second perspective is to understand how to perform qualitative analysis, evaluating results of generative science and models that create hypotheses distinct from results produced by traditional deductive and inductive techniques. Modelers need a better method than arbitrarily selecting rules and seeing if they expect models to work properly (Conte et al. 2012). Currently, creations of modeling and simulation processes are the result of expert intuition and are therefore a challenging task for novices, in part because generative science and qualitative analysis is similar to abductive logic (Klugl and Karlsson 2009). ABM faces a few challenges with regard to this perspective: how to avoid creation and testing of ad hoc rules and how to construct plausible models with conditions appropriate to create valid and desired output. The combination of the agents, their interactions, and the environment create emergent behavior and "grow" regularly observed macroscopic properties.

The third perspective is to understand methodologies and techniques for the integration, verification, and validation of heterogeneous models. The combination of each of these perspectives will enable a modeler to create valid models using ABM techniques. Nevertheless, challenges remain, such as collecting appropriate and necessary data and addressing the questionable science of a one-time test.

4.3.7 ABM and Design Patterns

Some of the challenges described within these 3 perspectives are similar to those encountered in computer science. For example, in software development, designers use a best-practice technique called design patterns to help make software design successful. However, some research has indicated that object-oriented patterns are not directly transferable to agent-based design patterns. Among other reasons, this may be due to differences in implementation languages and to differences in the level of abstraction (Oluyomi 2006; Klugl and Karlsson 2009; Klugl and Bazzan 2012). Moreover, the concept and use of individual agents often changes as model development progresses.

However, other research suggests agent-based design patterns are reasonable but acknowledge that the notion of model reusability is different from traditional software patterns. For instance, Ayodele Oluyomi suggests that the value of an agent-based design pattern is a function of proper definition and rigor, which includes attributes of the completeness of the model specification, clearly communicated understanding, identification of trade-offs, and appropriate application. He concludes that a 4-step process could be used as the basis of abstract model design: 1) agent-oriented analysis, 2) multiagent system architecture, 3) agent internal architecture, and 4) multiagent system realization. Michael Weiss's (2003) research influenced this proposal, suggesting that major components of a design pattern included context, problem statement, acting forces, a solution, and problem context.

Figure 21 is an adapted representation of Oluyomi's proposed design and modeling process:

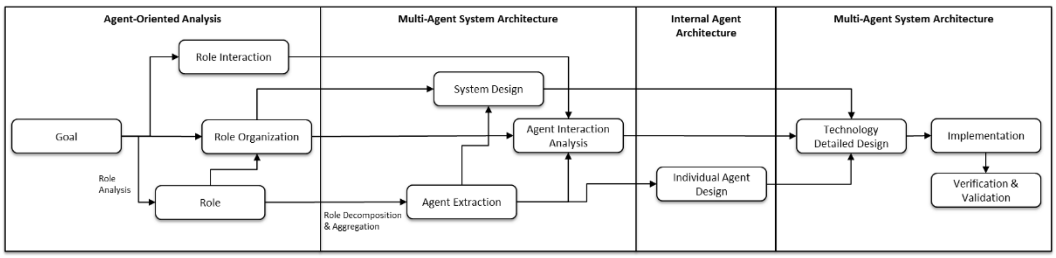

Fig. 21 An adapted representation of Oluyomi's proposed design and modeling process

4.3.7.1 Step 1: Agent-Oriented Analysis

The first aspect of model creation begins with an analysis of the model requirements, such as identifying goals, subgoals, and quality metrics used to evaluate model objectives.

Second, the model designer identifies all roles within the model. Roles characterize and define system-level roles, such as external human and software systems. Roles are not unique to individual agents; multiple agents may express a single role, or a single agent may express multiple roles.

Third, the model designer characterizes and organizes groups of agents expressing similar roles. This is a structural grouping of the roles contained within the model.

Fourth, the model designer identifies role interactions. Results of the initial goal analysis ensure that role interactions will reflect the relationships identified. Role-to-role relationships might exhibit collaborative, controlling, or competitive properties. In the case of a collaborative relationship, for example, a set of roles would work together to realize a common goal necessary for the model.

4.3.7.2 Step 2: Multiagent System Architecture

This design step begins with a specification of agents who represent roles within the model. Roles describe behaviors and interactions and are translated and extracted into agents.

Second, once agents are extract, the model designer tests the defined relationships and interactions to ensure that the expected interactions and behaviors between agents result from the model.

Third, the model designer introduces traditional software-engineering requirements with the system-design step. External data and systems may be accessed in this step. Additionally, the model designer specifies interfaces with external systems.

4.3.7.3 Step 3: Agent Internal Architecture

The internal agent step identifies where notions of autonomy, proactive behavior, reactivity, and social behavior are represented within internal agent logic. Depending on the roles agents need to exhibit, different property values may increase certain types of behaviors. Sample types of agents may include assistant, informational, collaborative, or mobile agents; the agent type determines individual architectures and how internal components are structured. Individual types of architecture include deliberative, reactive, and hybrid.

4.3.7.4 Step 4: Multiagent System Realization

This final step incorporates the prior 3 steps of design into an implementation. The model developer outlines development specifications and selects various considerations, such as implementation environment and programming language.

Second, implementation realizes the specified model. Integrated development environments may be used to assist the realization of the model. The model developer deals with implementation considerations during this step, such as ensuring the simulation runs fast enough.

Verification and validation is the final step, which involves examination of both the structural and interactive components of the model and proper output. Ideally, this step uses an iterative experimental design and testing.

4.3.8 Types and Attributes of Agent-Based Model Design Patterns

Using the aforementioned ABM flowchart design methodology, Oluyomi identifies the design process for defining and instantiating an agent-based model. However, there are a number of attributes included within each step. Oluyomi recognized these differences and identified the following observations in his research.

Figure 22 identifies each of the 4 steps in the left-most column, highlighted in bold. Next to each step are categories, describing the nature of the attributes that should be considered by the model designer. For example, the first row identifies the Agent-Oriented Analysis step, which identifies organizational and interactional categories of attributes. The organizational category describes real-life observations and goals for the model, and these attributes act as a way to structure components and interactions used in the model. In comparison, the interactional category describes the type and nature of the interactions between agents and how agents interact with each other.

Agent-Oriented Analysis	**Organizational**	**Interactional**	
• Roles / Multiple Roles • Organization of Roles • Interaction • Application Domain	• Roles • Goals • Coordination / Control • Associations / Relationships • Responsibility	• Interaction Objective • Interaction Type • Domain Rules • Interaction Rules • Distribution • Accessibility	
Multi-Agent System Architecture	**Definitional**	**Structural**	**Interactional**
• Roles and Agents • Multiple Agents • Arrangements of Agents • Quality Goals • Interaction / Communication • Constraints • Infrastructure	• Combination Rules • Division Rules • Goals • Responsibility	• Knowledge Repositories • Other Entities • Geometry • Bandwidth • Host Stability • Data Volume	• Control Flow • Introduced Agents • Message Exchange Rules • Message Format • Ontology
Internal Agent Architecture	**Structural**	**Interactional**	**Strategic**
• Single Agent • Agent Internal Components • Arrangement of Agent Components • Constraints	• Knowledge Component • Strategy Component • Interaction Component • Environmental Interface • Geometry	• Message Input • Message Output • Message Processing • Perception Handling • Action Execution • Environment	• Autonomy • Reactivity • Proactive Behavior • Knowledge Management • Adaptability
Multi-Agent System Realization	**Definitional / Technology**	**Other**	
• Data Definitions (Classes, Objects) • Dependencies • IDE, Programming Language • Sample Code • Function, Procedures			

Fig. 22 A listing of the attributes considered while creating and agent-based model based on Oluyomi's proposed design and modeling process

Each of the 4 design steps and categorical designations identify attributes influencing model considerations. For example, Agent-Oriented Analysis includes "interaction objective", which relates to the purpose of an interaction within a virtual organization. In another example, Multi-Agent System Architecture identifies "interactional categorization" attributes of "control flow", "introduced agents", "message exchange rules", "message format," and "ontology" that are applicable to this part of model design. Oluyomi goes on to identify and define each category and attribute in his research (2006).

Using a combination of the 4-step design process and the categorization of attributes relevant to each step, Oluyomi reviews 97 agent-oriented design patterns studied by 15 authors. Oluyomi selects 28 of those patterns, using an attribute-based analysis, and identifies their uses and applicability within his proposed design process. Figure 23 identifies and summarizes the results of the analysis and uses the same layout as Fig. 22, thus identifying design patterns applicable to categories within the design process (Oluyomi 2006).

Agent-Oriented Analysis	Organizational	Interactional	
	• Structure-in-5 • Joint Venture • Pyramid • Agent Society	• Agent as Mediator	
Multi-Agent System Architecture	**Definitional**	**Structural**	**Interactional**
	• Agent as Delegate	• Star-shaped Movement • Branching • Itinerary	• Contract Net Protocol • Embassy • Monitor • Wrapper • Agent as Mediator
Internal Agent Architecture	**Structural**	**Interactional**	**Strategic**
	• Basic Negotiating Agent • InteRRaP	• Sense and Infer • Ecological Recognizer	• Reactive Agent • Deliberative Agent • Opportunistic Agent • Interface Agent • InteRRaP • BDI • Sentinel
Multi-Agent System Realization	**Definitional / Technology**	**Other**	
		• Synchronizer • Environment Mediated • Behavior-based Decision • Master-Slave • Meeting	

Fig. 23 Oluyomi's list of identified design patterns categorized by their type of interaction and stage within the agent-based, model-creation-process model

4.3.9 Evaluating Agent-Based Models

Epstein identified motivations for creating models, such as explaining phenomena, guiding data collection, revealing dynamic analogies, discovering new questions, identifying central uncertainties, and providing insight into decision tradeoffs (Epstein 2008). Models can confirm whether macro-level observations are possible and explain the interactional phenomena, from which those observations result. However, once created, the modeler tests the model to determine whether it is operating as expected.

Paul Borrill and Leigh Tesfatsion (2010) proposed an 8-step process for testing and evaluating agent-based models. In their experience, they found researchers typically repeat the same process for experiments:

1. Develop an experimental design for the systematic exploration of a theoretical issue of interest

2. Construct a computer world, or a culture dish, consisting of a collection of constituent agents appropriate for the study of the theoretical issue

3. Configure the computer world in accordance with the experimental design

4. Compile and run the computer world with no external interference and record outcomes of interest

5. Repeat the same experiment multiple times, using different random-number-generator seed values, to generate an ensemble of runs to derive a distribution of world outcomes

6. Repeatedly iterate Steps 3–5 until the full range of configurations, specified under the experimental design, has been explored

7. Analyze the sample distributions for world outcomes and summarize theoretical implications

8. Use theoretical summaries to form hypotheses that can be potentially validated with historical or real-time data

Using this procedure, the modeler evaluates performance of the model by collecting data to evaluate relevance, simulating and validating performance, and performing a sensitivity analysis.

Hypothetical models test whether conditions are likely to produce expected phenomena; if so, they provide justification that a specific type of data or unknown phenomena may exist. However, collection of the appropriate data, which is necessary to validate models, can be difficult, especially when modeling individual human decision-making. Furthermore, the nature of collected data may affect how well the model can represent a situation. Referring to Axtell and Epstein's concept of "maturity level," if a model is designated and verified as maturity Level 4 (using Axtell and Epstein's Empirical Relevance Framework, Section 5) but precise data on constituent actors, modelled within the simulation, is not available, then the output of the model is not likely to be valid.

Data collection includes collecting model-produced data. Step 7 of the testing procedure identifies an analysis of macro- and micro-level characteristics, verified by simulated data. Depending on the modeler's needs, collected data may enable a statistical analysis of the system's characteristics. However, if the modeler's objective is to evaluate individual agents within the model, such as how they make decisions and how they interact with other agents, then more in-depth observation may be needed.

Simulation helps the modeler understand the consequences of agent interaction, while providing data for validation. Experimental design, identified in step one of the testing procedure, and the parameters used for a simulation may result in wide-ranging difference in the outcome of simulation results. For example, differences in spatial perception distances may result in widely varying results. Alternatively, the number of agents used within a simulation is another subtle variable, especially if the modeled phenomenon requires a minimum required number of agents and interactions to emerge. Thus, model validation is an essential aspect of the simulation process (Duong 2011). Ideally, the best-case scenario during validation is to use model parameters that have identifiable real-world meanings, as this allows a modeler to use and test reasonable and understandable ranges of values.

Finally, the evaluation process considers sensitivity of parameter variables. Sensitivity helps determine model robustness. Ideally, the modeler should consider and discover sensitivity by testing ranges of parameter values, as identified in step 6 of the testing procedure (Cioppa and Lucas 2007; Chandola et al. 2009; Viana 2013). Moreover, the modeler should consider the sensitivity of the model design itself, for example, as to whether a minor change in the model leads to large changes in the overall output. This is because small amounts of noise may actually contribute to the formation of unintended and emergent phenomena. As such, before the modeler characterizes simulation output, the simulation should to be run enough times for a statistical characterization. Each time, the initialization value of the random number generator should be changed so the effect of noise is constrained within the context of many simulation trials.

Once the modeler computes and analyzes tests, they become useful to other researchers if presented properly, ideally in a form that allows other scientists and researchers to reproduce results. For example, by distributing source code and/or pseudocode along with initial and boundary conditions, the kind of interaction network used, and model parameters. In addition, results of a variance analysis help convey intramodel dependence of parameters.

4.3.10 Limitations and Challenges of ABM

While ABM has the potential to model and provide insight into a variety of scenarios, it also has limitations. One limitation is in how the technique is viewed; namely, it is not a means to control social systems. Instead, Dirk Helbing states that agent-based modeling is a robust approach, which provides a way to transition from a “regulatory approach” to a mechanism that models the system (Helbing 2012). He suggests that regulations often correspond to changing boundary conditions but that agent-based modeling is a systems approach that models interactions in a way that reduces instabilities.

Axtell (2000, 2011) identifies other limitations, described as the inability to create high-fidelity models; predictions of point outcomes; small “n” forecasting; the quantitative comparison of tactics; and long-run prognostication (Turnley et al. 2012; Frank 2012, 2015).

- High-fidelity models describe model minutia and grow the simulated environment from small parts and their interactions. High-fidelity models compare to the common approach of limiting model scope to the specific question asked.

- Prediction of point outcomes identifies the limitation of forecasting a specific event occurring at a specific point (e.g., in space and time). Instead, agent-based modeling is used to characterize the range of possibilities of such an event occurring.
- Small “n” forecasting describes the problem of running simulations where there are not enough data available to verify and validate the model results.
- The quantitative comparison of tactics identifies the inability to compare and contrast irregular-warfare tactics with the models available presently.
- Long-run prognostication identifies the difficulty of identifying the future state of situations because of the cumulative effect of small perturbations to the system over time.

Another challenge to creating valid models is their dependence on the availability of appropriate data. A common approach during model development is to limit model creation to the scope of the question asked. This bears out Occam’s razor that a model should be as simple as possible but not simpler (Gigerenzer and Todd 1999; Axtell and Young 2004; Guerin and Kunkle 2004). However, depending on the intended model use, models are ideally evaluated quantitatively at both micro- and macrolevels. An accurate representation of both these levels, however, generally indicates a large amount of specific data. Therefore, while the potential of agent-based models is high, a careful consideration and management of expectations is appropriate to balance its value.

A future area of development in ABM will focus on modeling behavioral and cognitive interactions, such as social process models like tribal dynamics, which are currently difficult to model. In the future, challenges will continue to arise as methods, tools, ethics, and privacy concerns influence the collection and testing of such models. Additional challenges exist in facilitating cooperation between complementary fields of study, notably the social sciences and computer science. Yet, there are few defined and managed educational paths for computational social scientists.

5. Existing Research and Applied Development of ABM

ABM capabilities have been developed and integrated into several programs and tools. This section aims to provide an overview of the state-of-the-art tools for ABM, surveying existing defense capabilities that incorporate agent-based techniques, reviewing the evaluative criteria for determining research maturity level and introducing the concept and components of the Human Domain, and surveying published ABM research with respect to the Human Domain.

5.1 ABM in Existing Defense Capabilities

During tactical decision-making, some decisions consider the results of actions, which are kinetic, while others are nonkinetic or observational in nature. Kinetic courses of action include the employment of individual weapons systems, force maneuvers, fires, and analyses of weapon effects. Observational and other nonkinetic activities include intelligence, surveillance and reconnaissance, engineering operations, and logistics and sustainment. Moreover, in an irregular warfare or urban context, nonkinetic courses of actions include analysis of information operations and civil operations (Frewer 2007).

Analysts evaluate both kinetic and nonkinetic courses of actions using a combination of methodologies, which might be broadly considered as physics- and social-science-based methodologies. Physics-based methodologies depend on a well-defined mathematical analysis of variables such as terrain features, weapons capabilities, and the numbers of personnel and equipment. Social-science capabilities may use mathematical methods and variables, but in these methodologies values are qualitative rather than quantitative. For example, social-science analysis might base its computation on the statistical interpretation of surveys, on the cultural analysis of experts, or on organizational dynamic analysis. Figure 24 illustrates the differences between the earlier types of analytical methodologies and objectives.

The combination of kinetic action and physics-based analysis, shown in the top-right quadrant of Fig. 24, plays an important part in helping commanders evaluate COAs, which concern executing offensive operations. Similarly, analysts combine kinetic action and social-science analysis to identify and model second- and third-order consequences and effects of actions. Such an analysis may consider the population’s reaction to the removal of a target and to the methods used.

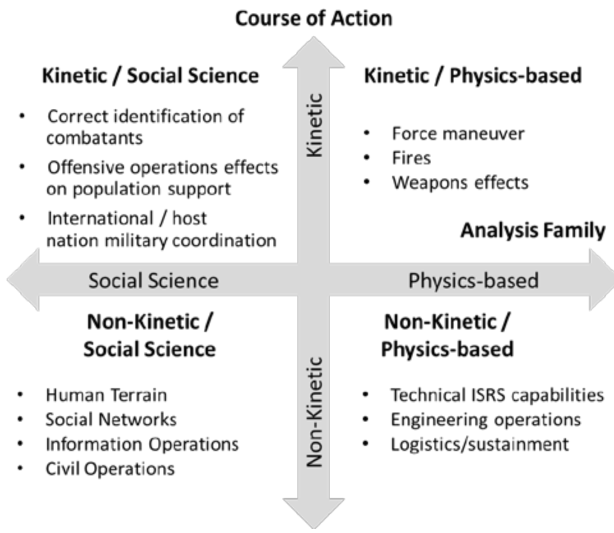

Fig. 24 A quad chart illustrating 4 quadrants of tactical analysis (Connable et al. 2014, p. 23). This study's emphasis on applications of ABM to tactical wargaming thus limits its scope to the bottom-left quadrant, "Non-Kinetic/Social Science".

Combining nonkinetic and physics-based analysis helps in the allocation of intelligence, surveillance, and reconnaissance assets, the prioritization of engineering activities, and the identification of risk for logistics and sustainment. Finally, analysts evaluate the results of combining nonkinetic and social-science analysis with respect to the design of information operations, the coordination of whole-of-government approaches, and the communication of cultural interpretation. They typically communicate these results using frameworks such as PMESII-PT, DIME, and ASCOPE in an ad hoc manner (Counterinsurgency Training Center–Afghanistan 2010, 2011). However, "military professionals describe this volatile mix of factors (i.e., the variables within each of these 3 frameworks) as being ambiguous, complex, uncertain, and ill-structured. When trouble appears, there is no consensus about what the fundamental problems are, how to solve them, what the desired 'end state' should be, and whether an 'end state' is achievable or not" (Connable et al. 2014, p. 29). This suggests that there is still a need to understand how variables interact and understand their possible consequences (Perez 2011).

5.1.1 Tools and Capabilities

This section surveys state-of-the-art tools and capabilities identified as embodying an agent-based capability or other similar type of capability. These tools emphasize the nonkinetic and social-science quadrant identified in the previous section. In Fig. 25, the tools are listed in an order that illustrates the progression of and interest in agent-based capabilities over time.

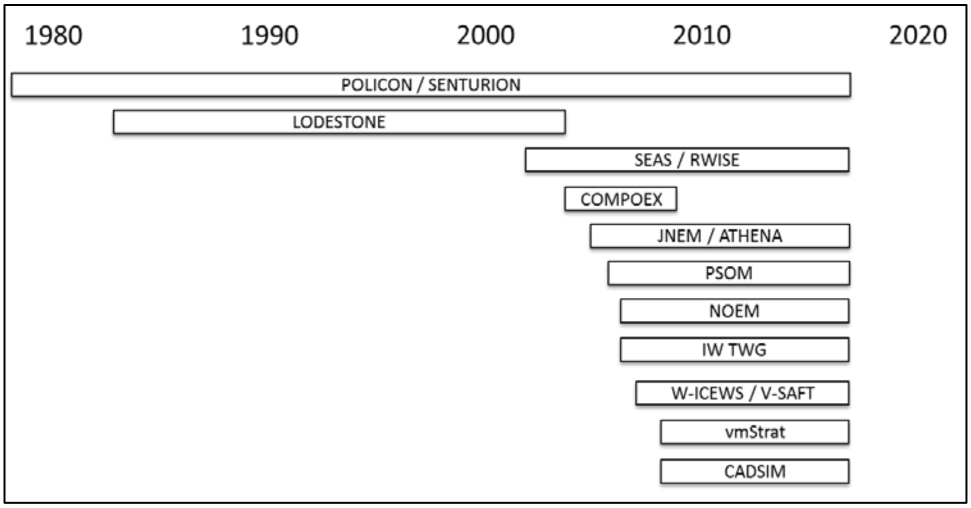

Fig. 25 An estimated timeline of tools embodying ABM capabilities. Dates in the illustration are approximate.

5.1.2 Policon/Senturion

Policon is a tool that was developed by Bueno de Mesquita in the late 1970s and early 1980s (Larson et al. 2009, p. 47). It uses algorithms from game theory, decision theory, spatial bargaining, and microeconomics to analyze political dynamics, modeling how competing agents change policy positions over time (Bueno de Mesquita et al. 1999; Schneider et al. 2010). The tool computes the interactions and decisions of actors based on their own perspectives of situations and, as such, an individual actor's perceptions of a situation can vary greatly from other agent perceptions of the same situation (Bueno de Mesquita 2010). The tool supports strategic-level analysts and decision-makers.

Input into the model is specified by SMEs and includes key stakeholders, a range of policy alternatives, policy preferences, the estimated capability each stakeholder may employ, and the estimated importance each stakeholder assigns to each policy (Fischhoff and Chauvin 2011). Once an analyst computes a baseline interaction, he or she explores changes to agents' positions and importance in an effort to discover how to improve the political outcome.

The CIA has reportedly used the Policon model and has concluded that the model has been correct in over 90% of the real-world applications for which it has been used. In those cases where the model forecasts differed from those of SMEs, it was the Policon forecast that was correct (Cioffi-Revilla and O'Brien 2007, p. 32).

Senturion is an evolution of the Policon tool used at the National Defense University (Kennedy 2014, p. 1). It is a simulation capability that analyzes the political dynamics within local, domestic, and international contexts. It predicts how the policy positions of competing interests will evolve over time (Abdollahian et al. 2006). Senturion analyzes behavior of actors who influence political outcomes by examining interactions through simulation. Like Policon, SMEs identify input parameters that include stakeholders, their positions, and the estimated importance of outcomes. It applies a game theoretic perspective and assumes that all agents maximize their interests and seek to form likeminded coalitions. Senturion also provides a user interface to visualize results of estimated interactions.

5.1.3 LODESTONE

LODESTONE is a RAND-developed tool that relies on the axioms of spatial politics, strategic game theory, expected utility theory, and rational-choice theory (Connable et al. 2014, p. 130). The capability originated as a Defense Advanced Research Projects Agency (DARPA)-sponsored research and development project in the 1980s and later upgraded in 1997. The model exhibits 3 features: 1) the ability to identify the most likely outcome, 2) the ability to calculate the expected utility (i.e., desired outcome) from changing interactions with another agent, and 3) the ability to reiterate agent interaction results until a stopping criterion is met.

5.1.4 Synthetic Environment for Analysis and Simulation (SEAS) /Reference World Information and Simulation Environment (RWISE)

In the early 2000s, the SEAS capability was developed and later modified to represent effects-based operations for Joint Forces Command (JFCOM) (Chaturvedi 2004; 2007; 2009; Snyder and Tolk 2006). Effects-based operations evaluate and consider the broader consequences of military operations (Maxwell and Carley 2008). SEAS does this by using an agent-based modeling technique, which integrates socio-psychological and organizational-behavioral models at the individual, organizational, institutional, infrastructure, and geographical levels (Prevette and Snyder 2004). The simulation uses combinations of heterogeneous agents and includes individuals, organizations, institutions, and infrastructure.

Analysts communicate with SEAS using PMESII and DIME constructs, and the simulation has been used for strategic and operational communication. For example, courses of action defined in terms of DIME variables can model actions defined with the PMESII taxonomy and can attempt to quantify the impact of such actions. Joint Warfare Systems (JWARS) is a complementary simulation capability that models both red and blue forces and quantifies the impacts of military actions. For example, JWARS can model up to a million buildings with their own PMESII designations. The JWARS simulator and SEAS contain messaging capabilities, so both models can communicate while focusing on modeling their respective and specific phenomena.

RWISE is an evolution of the SEAS capability, with the goal of building a synthetic "mirror" of the real world. Automated data sources such as news feeds, opinion polls, demographic statistics, economic reports, and social media are fed into the system. Automatic calibration algorithms inform the RWISE system which scenarios, identified in prior time steps, are no longer valid so RWISE can prune those possibilities. In 2006, JFCOM's Urban Resolve 2015 experiment tested RWISE in a synthetic environment (Cerri and Chaturvedi 2006; Anastasiou 2006).

5.1.5 Conflict Modeling, Planning, and Outcomes Experimentation Program (COMPOEX)

COMPOEX began in 2004 as a collaborative project sponsored by DARPA and JFCOM to develop technologies that could enhance the capability of leaders and staffs to plan and execute major operations in a complex environment (Kott and Corpac 2007; Waltz 2008). Ideally, such decisions would consider PMESII.

The project was the composition of 4 experiments: 1) effects identification, 2) domain visualization, 3) operation planning, and 4) parallel planning (Kott et al. 2010). The effects identification experiment analyzed whether a range of options, such as actions against certain nodes or changing the timing and sequence of actions, would result in the intended actions. Domain visualization tested whether PMESII data was effective in helping teams understand complex domain information. Operation planning evaluated whether COMPOEX-developed tools would enhance creation of an interagency operation plan. Parallel planning evaluated whether parallel processes could effectively result in several named operational effects.

The underlying technologies of the tested tools in this project were a mixture of agent-based models, systems dynamics, Bayes Nets, discrete time models, Petri Nets, and Markov models. The primary contractor, BAE Systems, created a library of models, each instantiating an aspect of the PMESII model (Waltz 2010). For example, systems dynamics and linear programming techniques were used to model infrastructure components. However, political components were the only components to use agent-based models.

Lessons learned from COMPOEX evaluations mainly focused on human interaction and expectation management rather than on technological items. Pre-experiment training is a strict necessity and experiment design needs to exhibit individual and specific interagency cultures. Moreover, the nature and interaction between interagency members and organizations need to be well understood in order for broad collaborations to be successful.

5.1.6 Joint Non-Kinetic Effects Model (JNEM)/Athena

JNEM is a tool developed by NASA's Jet Propulsion Laboratory (JPL) for US Army brigade, division, and corps commanders operating in Stability and Reconstruction Operations during 2005 (Ripley 2008). In 2009, JPL released an updated version of the tool named Athena, with the goal of creating a single-user decision support tool with a multiyear planning horizon. By early 2012, JPL released the third version of Athena, which models the interaction between ground forces, demographics, attitudes, politics, economic and information (Duquette 2012; Chamberlain and Duquette 2013).

Athena simulates situations at the strategic and operational levels. The analyst is responsible for entering all inputs. According to user reports, it takes about 4 months to run a complete cycle, which includes gathering data validated by an SME and the potential end-user (Connable et al. 2014). Inputs include defining actors and their resources, belief systems, and strategies. They also include civilian, force, and organization groups, and their respective satisfaction levels. Models of the neighborhood and environment are also defined. After the operator identifies all of the inputs, the simulation is run; at the operator's discretion, "magic" capabilities may be interjected, and attrition may be adjusted to account for noncombat deaths, attitude changes, and environmental situations.

Athena is a tool included in the Army's One Semi-Automated Force (OneSAF) simulation suite (Boiney and Foster 2013). Within OneSAF, Athena helps represent the interaction of PMESII and DIME effects on the operational environment over time (Brecher 2014). It helps the analyst understand the impacts of operations, including possible second-, third-, and higher-order effects.

5.1.7 Peace Support Operation Model (PSOM)

The UK's Ministry of Defence, Defence Science and Technology Laboratory (DSTL) developed PSOM in 2006 as a simulation-based wargaming tool designed to help decision-makers consider populations affected by irregular warfare. As such, PSOM incorporates attributes of civil and military components, crisis management, and security and stabilization operations (Brecher 2014). DSTL created the tool after British participation in the Iraq and Afghanistan wars, identifying a need for a better understanding of conflict stability.

DSTL designed PSOM to simulate situations at the strategic and theater levels. PSOM uses a combination of 2 processes, a Strategic Interaction Process and an

Operational Game, to simulate interactions. The Strategic Interaction Process simulates strategic level decision-making, such as those by political and military leaders. The Operational Game translates those decisions into campaign effects. Both processes simulate military battle groups and civil reconstruction groups carrying out their designated activities with the objective of identifying how policy decisions, strategic decisions, and operational effects are interrelated.

The PSOM sequence of events is as follows: 1) develop the course of action, 2) evaluate the course of action, 3) run a simulation turn, 4) receive the situation update, 5) discuss the results, and 6) repeat. PSOM operates with the assumptions that a population's behavior changes slowly and that each time step is one month. During the input process, players may interact with each other to simulate diplomatic and political activity in the real world. An analyst then feeds the input information into the simulation. Inputs consist of the following: 1) all factions in the campaign, 2) the environment, 3) the infrastructure, 4) the population, 5) the economy and employment, 6) political-level interactions, 7) military units and combat, 8) reconstruction and civilian units, and 9) human and other soft factors. Plans are scripted and all actors proceed according to plan for the full month; PSOM adjudicates outcomes of agent interactions stochastically. Outputs consist of 1) civilian casualties, 2) security, 3) consent, 4) initiators of kinetic events, and 5) readiness levels.

According to DSTL, analysts have used PSOM several times to support planning decisions, finding that the tool was appropriate as a "useful conversation piece" and helped stakeholders think through situations. However, PSOM is a time- and data-intensive wargame and requires many different players to represent scenarios, which may make it impractical for time-sensitive tactical scenarios.

5.1.8 National Operational Environment Model (NOEM)

NOEM is a strategic analysis/assessment tool that provides insight into complex operational environments (Salerno 2010; Sudit et al. 2015). The US Air Force's Rome Laboratory developed NOEM in conjunction with Sandia National Laboratories, Johns Hopkins University Applied Physics Laboratory, the Massachusetts Institute of Technology, and the University of Texas at Austin. NOEM supports baseline forecasts by generating plausible futures based on the current state. It supports what-if analysis by forecasting ramifications of potential "Blue" (i.e., friendly) actions on the environment, including unintended consequences in the short and long term. NOEM supports sensitivity analysis by identifying possible pressure points and their relative sensitivities to stabilize a region or nation.

NOEM can assist decision-makers, analysts, and researchers with understanding the interworkings of a region or nation state, the consequences of implementing specific policies, and the ability to test new operational-environment theories. NOEM models the environment as a nation-state with the ability to connect multiple regions. The model uses stability-operations theory as the basis of its interactions and supports DIME and PMESII variables. NOEM models people based on age, interest group, affinity, and occupation; it also supports social and cultural interaction and understanding.

5.1.9 TRADOC's Irregular Warfare Tactical Wargame (IW TWG)

IW TWG was developed by TRADOC Analysis Center beginning in 2008 as an outgrowth of the PSOM capability. It focuses on human behavior and social and cultural factors, analyzing the effect that different courses of action have on civilian population attitudes. It is developed in conjunction with the Center for Naval Analyses, TRADOC G2, Naval Postgraduate School, Texas A&M University, Argonne National Laboratory, Charles River Analytics (CRA), University of California at Davis, Army Materiel Systems Analysis Agency, and others (Duong et al. 2011; Duong and Bladon 2012; Works 2015). The intended users of the tool include operational users at the brigade, battalion, and company commander level (Brecher 2014). Context includes interactions between ground forces and civilians and key leaders and infrastructure.

IW TWG consists of several components: 1) an operational wraparound, 2) planning, adjudication, and visualization environment, and 3) cultural geography and nexus-network learner models (Duong 2009a, 2009b, 2012, 2013; Duong and Pearman 2012). The first component simulates command and control function and incorporates infrastructure and population atmospherics. The second component allows players to plan, access, and record tactical-level inputs such as local leaders, population, and infrastructure interaction. The third component provides population responses to events. IW TWG is designed to simulate one or more weeks of time, with human, social, cultural, and behavioral attributes as domain features.

Data input into the system includes population, key leaders, local infrastructure, and population responses to actions. IW TWG then uses SME input to verify inputs. Gathering data for the data entry process, including verified inputs, can take around 9 months. Similar to other simulation models, a specific scenario output is one of many possible outcomes and is not an exact forecast.

5.1.10 IW TWG: Cultural Geography Model

In 2006, development began on the Cultural Geography capability, later used within the larger IW TWG modeling tool. Like several of the tools discussed, the capability uses agent-based modeling to represent interactions between agents. It seeks to address analysis issues within the context of an irregular warfare setting, and interactions are based upon Army and Marine COIN and Stability Operations doctrine (DA 2011). Agents within the system interpret information through their own perceptions of beliefs, values, and interests (Alt and Lieberman 2010; Alt et al. 2010). The theory of "narrative paradigm" is used to instantiate agent models to include identity and individual agent history (Alt et al. 2009). Analysts use a combination of survey data and SME input to derive agent attributes. The advantage of using this theory is that agents are semirational actors, in that they rely on their beliefs about the world; this is an advantage because modeled situation better represents reality (Wakeman 2012). Moreover, the theory of "planned behavior" guides individual agent actions, describing the relationship between an agent's individual attitudes toward different behaviors, his or her perception of the relationship of social norms to behaviors, the individual efficacy of his or her given behavior, and his or her intention to take an action (Ajzen 1991).

5.1.11 IW TWG: Semi Automated Force (SAF)

Researchers at the University of California at Davis developed another tool for IW TWG that automates the selection of "Red" (i.e., enemy) courses of action. The Human Social Culture Behavior (HSCB) modeling program developed the capability and then it was transitioned into the IW TWG suite. The tool makes choices based on historical data about players and on their standard operating procedures, the commander's preference for kinetic versus nonkinetic tasks, and the commander's preferences to automatically select tasks (Boiney and Foster 2013).

During a wargame, the SAF tool speeds up red task selection to allow more time for planning. Input data include the executed tasks of all players, the red players' scheduled tasks, the population's attitudes and behavior, and the population density. These data produce a list of predicted tasks that red forces will undertake in the following week.

5.1.12 IW TWG: Military Information Support Operations (MISO) Planner

The MISO Planner tool was developed by CRA for the HSCB program and transitioned into the IW TWG suite. Originally, CRA developed the capability for the Air Force as a program called Organizational and Cultural Criteria for Adversary Modeling, which evolved into the Susceptibility and Vulnerability Analysis Tool. Military information-support operations, formally known as psychological operations, are one of several courses of action a planner may consider while modeling civil interactions.

The MISO tool allows the user to create a computational model of an adversarial, friendly, or neutral population. The tool helps the user assess and verify causal reasoning, communicate the reasoning decision process, forecast future behaviors, and analyze consequences of course of actions (Air Force Research Laboratory 2011).

The IW TWG Cultural Geography model produces observable attitudes and behaviors of populations, which the MISO tool accepts as input, in addition to a list of scenario events. The analyst then selects the message for the intended demographic. The tool output includes a list of tasks, the message, delivery mode, location of delivery, and timeline.

5.1.13 Complex Operational Environment Model (COEM)

COEM was developed out of IW TWG and is intended for modeling theater and higher operational levels. COEM attempts to model extended-duration campaign effects. It does this by modeling the interactions among PMESII-PT variables rather than concentrating on the individual variables themselves. COEM decomposes each PMESII-PT variable into a number of subcomponents, based on social science theories and SME inputs, to enable wargaming staffs to better understand how Human Domain variables interact with its subcomponents and external stimuli (Brecher 2014).

5.1.14 COEM: Complex Military Mission Environment (CM2E)

The CM2E extends the COEM model by integrating a stochastic, closed-form simulation. This tool alters the human-interaction workflow by producing results through simulation instead of relying on the wargaming staff to specify them. Environmental states may change based on those simulation results (Brecher 2014).

5.1.15 Worldwide-Integrated Crisis Early Warning System (W-ICEWS)

The W-ICEWS tool was developed by Lockheed Martin’s Advanced Technology Laboratories, beginning in 2007 as a DARPA project, and demonstrated the possibility of forecasting events of interest in different countries (Ruvinsky et al. 2014; Kettler 2015; Kettler and Lautenschlager 2016). The tool was developed in conjunction with Duke University, Innovative Decisions, Lustick Consulting, Pennsylvania State University, Strategic Analysis Enterprises, and Raytheon BBN Technologies. The tool is used at the strategic level as a social radar capability (Maybury 2011).

The W-ICEWS system monitors open-source information and uses that information to monitor, display, and forecast assessments at the national level. It is a composite of several components including a data processing and annotation capability (iDATA), a regional trend and sentiment capability (iSENT), a situational understanding and implication capability (iCAST), and a visualization capability (iTRACE). The iDATA annotates the "who, what, where, and when" using a combination of shallow and deep natural language-processing technologies (Corby 2015). Various integrated capabilities identify entities and events from within the source data. The iCAST interprets annotated data and forecasts events that contribute to instability in identified countries. It uses a combination of statistical and agent-based models to generate aggregate forecasts (Mahoney et al. 2011). The iSENT measures attitudes and perceptions about issues, people, and events and the propagation of attitudes across the Internet. The iTRACE provides a means to visualize trends and patterns and allows the user to identify time series and relationships. It also allows the user to view the underlying data sources.

The iCAST calibrates agent-based models to the current state of the modeled country and characterizes possible output to produce multiple trajectories of potential future states for that country. The actions and interactions of the agents within the ABM are based on rules and environmental conditions that describe the country and its sociopolitical theory. For example, all of the political models stem from a generic political model that captures rules based on political theory for country-specific actions, such as protest, rebellious activity, and religious violence. As planners recognize and comprehend the political theory at play, using the country's environmental conditions to provide input into the initial state of the agent-based model, the model enables them to understand a variety of potential future states and thus potential conflict futures for the country in question.

5.1.16 Virtual Strategic Analysis and Forecasting Tool (V-SAFT)

An agent-based capability developed by Lustick Consulting to support the DARPA ICEWS project, V-SAFT demonstrates the plausibility of forecasting events of interest (Lustick 2012; Egeth et al. 2014, p. 344). The tool is a forward-looking social radar that estimates the likelihood of events, such as domestic political crisis, insurgency, rebellion, and ethnic or religious violence (Alcorn et al. 2012; Chandra 2012; Garces and Alcorn 2012; Ward et al. 2013).

Figure 26 depicts the V-SAFT architecture, which is composed of 3 phases consisting of model building, experimentation, and analysis. During the model-building phase, each modelled country's geographical and administrative regions are translated into a pixilated spatial grid. Then, a combination of social-science theories and data (e.g., demographic, cultural, electoral, economic, and SME input, such as the elite network) are used as inputs into a Generic Political Model. Because it is integrated with W-ICEWS, the tool receives data as input, including elections, censuses, and SME reports, every month.

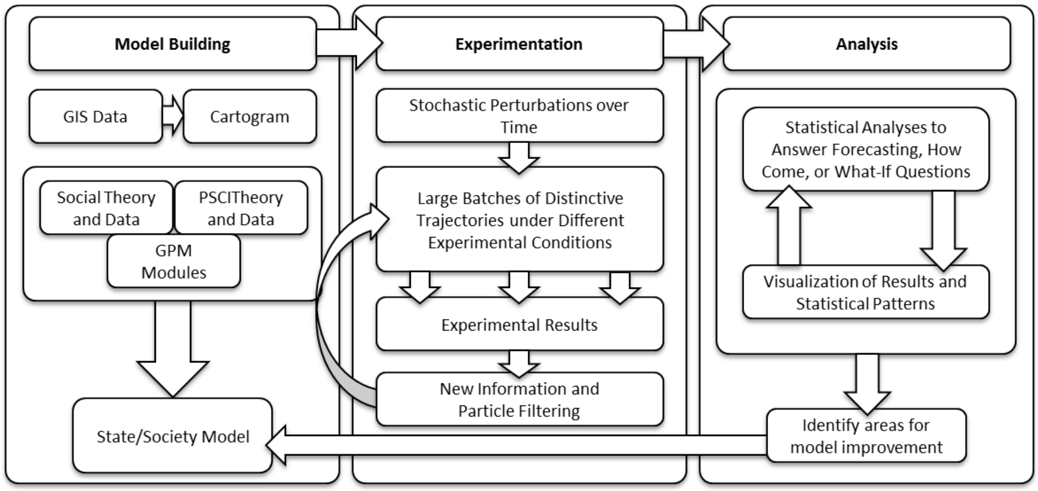

Fig. 26 The V-SAFT architecture and implementation phases. The V-SAFT capability is used within W-ICEWS to create and configure country-specific models.

During the Experimentation phase, models are instantiated with between 1,000 and 4,500 agents per country, followed by a brief initialization period. Once initialization is complete, simulated time progresses at approximately weeklong steps for one year. This simulation repeats 1,000 times to create distinct simulation results. V-SAFT ensures simulation results are unique by randomizing the distribution of agent attributes and by introducing small permutations into individual agent biases.

Finally, the analysis phase displays and compares monthly results to determine trends within the modeled country. Results from the current month identify probable, plausible, or possible outcomes. Forecasts are provided in a narrative and textual form for the analyst to read; additional information is made available if the analyst desires it. The objective of these results is not to provide an actual predicted future but to provide quantifiable and time-sensitive indications and warnings about specific types of events of interest.

5.1.17 Versatile Multiscale Strategist (vmStrat)

The vmStrat modeling framework is an ABM capability developed under the HSCB program. The principal investors originally created one of the more mature ABM frameworks, Repast, and vmStrat appears to be a related interactive framework for modeling actor interactions at multiple scales. For example, actors may represent states, alliances, substate institutions, parties, and so forth. It is designed so the user can experimentally and interactively create a model representing the current scenario. Likely, vmStrat has the potential to model Human Domain interactions but would need a mature operational concept, including additional agent attributes and interrelations (Brecher 2014).

5.1.18 COA Analysis by Integration of Decision and Social Influence Modeling with Multi-Agent System (CADSIM)

In support of the HSCB Program, Perceptronics Enhanced developed CADSIM to explore and model the effects of different COAs. It is a turn-based simulation tool, which forecasts models of interaction between actors, specifically modeling possible responses to COAs. CADSIM models actors and their attitudes, biases, and behaviors using Social Influence Network Theory.

SMEs identify inputs for CADSIM. They identify the actors to model, including relevant individuals, groups and populations, and political entities such as states, international organizations, and nonstate armed and criminal groups. SMEs also define the nature and strength of relationships between actors. Moreover, they develop each actor's decision model based on a consideration of the actor's socio-cultural, political, military, interests, strengths, and biases.

CADSIM outputs are ranked probabilistically and indicate a range of outcomes, if assumptions and hypotheses are valid. However, CADSIM does not emphasize Human Domain considerations. Additionally, author bias is possible because of the difficulty in assessing the degree of objectivity in data, design, and COA options. While testing the tool, experimental users have noted it may be difficult to configure if the operator is not already familiar with how to use the tool (Brecher 2014).

During CADSIM's development, the Air Force Targeting Center acted as a transition partner and provided operational use cases (Boiney and Foster 2013). The goal of the enhanced CADSIM framework is to allow planners to identify critical points of social interaction, and the likely influence of nth-order communication effects on different COAs.

5.2 Evaluating Agent-Based Technologies: Maturity Level and the Human Domain

Agent-based technologies are a combination of pre-existing research and enabling technologies, and each initiative has different degrees of maturity according to their objectives. This section identifies the criteria the study uses to evaluate and categorize research and then summarizes and identifies publically available agent-based research. The study uses a combination of Human Domain definitions, as identified by Brecher (2014) for SOCOM, and an agent-based model maturity framework identified by Axtell and Epstein (1994).

5.2.1 Evaluation of Maturity Level

Each of the agent-based research and technological capabilities discussed in this report has its own degree of maturity. The following evaluation scale provides a measure by which the authors graded and ranked identified capabilities. The scoring method has 5 possible states:

1. **Does not meet the need**: In this case, the research or technology is not likely to be an appropriate resource in modeling or developing the intended Human Domain capability

2. **Could be an external reference or example**: In this case, the research or technology could be a resource in modeling or developing the intended Human Domain capability; however, it is not likely to be a strong starting point

3. **Starting point for modeling the need**: In this case, the research or technology meets the threshold where it could be used as a starting point for additional research, without requiring the development of another independent capability, or as a starting point to begin modeling the intended Human Domain capability

4. **Exceeds the need**: In this case, the research or technology exceeds the threshold of an initial starting point and somewhat represents a modelled Human Domain capability

5. **Ideally suited for the need**: In this case, the research or technology demonstrates a well-modelled Human Domain capability

The authors use the previously stated evaluative criteria alongside the Axtell and Epstein maturity model to evaluate research. As discussed in Section 3, Axtell and Epstein identify a 4-level Empirical Relevance Framework ranging from Level 0 through Level 3, as shown in Fig. 27. Over time, Axtell has expanded this framework to include comparisons of docking, system engineering, policy, and the amount of data and time required (Axtell et al. 1996). For the purpose of this study, the authors added 5 evaluation criteria stated within the column "Research Relevance to Human Domain."

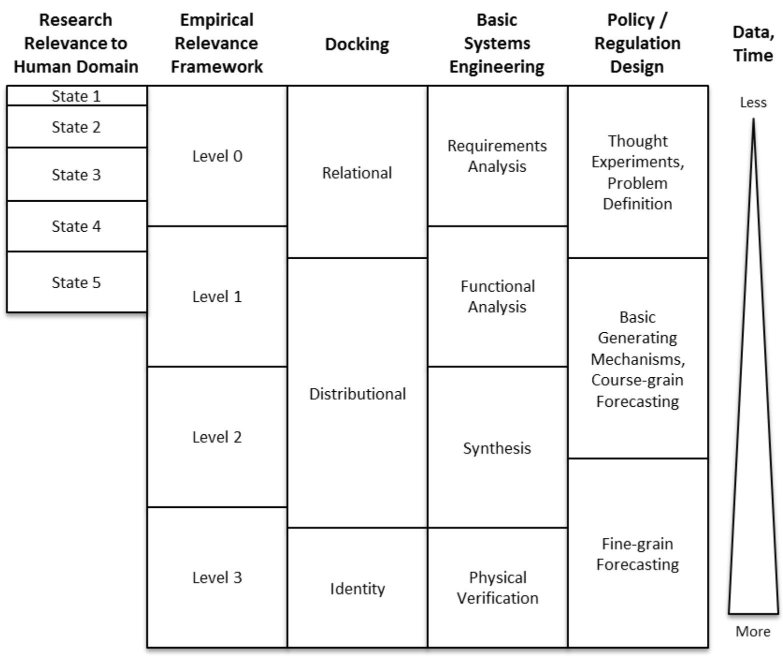

Fig. 27 Axtell and Epstein's Empirical Relevance Framework describes the maturity of agent-based models, ranging from realistic caricatures to quantitatively characterized phenomena at the microlevel. This illustration also incorporates docking, system engineering, policy/regulation design, and estimated data and time required (Egethet al. 2014, p. 290).

5.2.2 Human Domain Elements

The Human Domain concept is a construct that identifies elements necessary to understand human decision-making (Brecher 2014). The concept is comparable to other communicative frameworks, such as PMESII or ASCOPE, but, as might be expected, better describes the Human Domain (US Special Operations Command 2015). The study uses this categorization taxonomy to categorize existing agent-based research.

Brecher identifies 5 elements to the Human Domain concept: 1) social, 2) cultural, 3) physical, 4) informational, and 5) psychological. Social elements are structures and relationships among groups and institutions, often involving competition for influence and efforts to impose interest and perspectives. Cultural elements are a society's beliefs, customs, and way of life, and their impact on people's behavior. Physical elements are those natural and manmade attributes, which shape individuals' priorities. Informational elements are the sources, availability, and substance of data. Psychological elements describe how people evaluate and act upon information, including patterns of exercising judgment and reasoning in response to available facts. Each of these elements is described in the following text with additional detail by their respective subelements; this text is not comprehensive but rather illustrates the intended concepts.

5.2.2.1 Social

The following subelements—public groups, state institutions, local governments, civic groups, and societal groups—make up the social element. Public groups are gatherings of people drawn together by a specific cause but are not officially organized. They are distinct from organized civic groups. A state institution includes the state government and its connected entities, such as a Department of Motor Vehicles, Taxation, Social Services, and so on. The local government includes city, town, and village governments and its connected institutions, such as the department of public works, the police, and so forth. Civic groups include nongovernment groups who interact with people on specific issues such as poverty, welfare of animals, or regarding support of medical cause issues. A societal group includes gatherings for religious services and for social well-being (Brecher 2014).

5.2.2.2 Cultural

The following subelements—ideology, tribalism, customs or beliefs, ethnicity, religion and rituals, language, and communication—comprise the cultural element. Ideology is a set of conscious and unconscious ideas, which help define a person's goals, expectations, and motivations. Often, they are a set of standards considered to be normal behavior. Tribalism is a set of organized persons; tribalism may refer to a way of thinking or behaving in which people are more loyal to their tribe than to their friends, their country, or any other social group. Tribalism also implies the possession of a strong cultural or ethnic identity that separates a member of the tribal group from the members of another group. Based on strong relations of proximity and kinship, members of a tribe tend to possess strong feelings of identity. Customs are beliefs or behaviors passed down within a group or society, generally with symbolic meaning or special significance and with origins in the past. An ethnic group is a socially defined category of people who identify with each other based on common ancestral, social, cultural, or national experience. Unlike most other social groups, ethnicity is primarily an inherited status. Membership of an ethnic group tends to be defined by a shared cultural heritage, ancestry, origin myth, history, homeland, language and/or dialect, and symbolic systems such as religion, mythology and ritual, cuisine, fashion, art, and physical appearance. Religion and rituals refers to the system of religious beliefs and rituals practiced by a tribe or group of people. Language is the spoken word of a group or groups of people. Communication is the means of exchange of ideas, thoughts, and intentions among people (Brecher 2014).

5.2.2.3 Physical

The following subelements—geography, topography, hydrology, urbanization, resources, and climatology—make up the physical element. Geography examines the natural environment and how organisms, climate, soil, water, and landforms produce and interact. Topography is the field of geoscience comprising the study of surface shape and features of the earth; it also includes surface shapes and features. Topography, in a narrow sense, involves the recording of terrain, the 3-D quality of the surface, and the identification of specific landforms. Hydrology includes studying the movement, distribution, and quality of water including the hydrologic cycle, water resources, and environmental watershed sustainability. Urbanization is the population shift from rural to urban areas and the ways in which each society adapts to that change. It is the main process by which towns and cities are formed and become larger as more people begin living and working in central areas. Resources are sources or supplies from which benefit results. Typically, resources are materials, energy, services, staff, knowledge, or other assets that produce benefit and may be consumed or made unavailable. Climatology is the study of climate, defined as weather conditions averaged over a period (Brecher 2014).

5.2.2.4 Informational

The following subelements—means, message, and audience—make up the informational element. Means are the methods of transferring information among people, such as the use of the Internet, print media, radio, television, or person-to-person communication. Message is the information transferred through such means. Audience is the group or groups to whom the message is directed (Brecher 2014).

5.2.2.5 Psychological

The following subelements—cognition, awareness, perception, and reasoning—make up the psychological element. Cognition is the set of all mental abilities and processes related to knowledge, attention, memory, judgment and evaluation, reasoning, problem solving and decision-making, comprehension and production of language, and so on. Awareness is the ability to perceive, feel, or be conscious of events, objects, thoughts, emotions, or sensory patterns. Perception is the organization, identification, and interpretation of sensory information to represent and understand the environment. Perception is active and shaped by learning, memory, expectation, and attention. Reasoning is the capacity to consciously make sense of things, apply logic, establish and verify facts, and change or justify practices, institutions, and beliefs based on new or existing information. In addition, reasoning includes judgment and critical thinking. Judgment supports reasoning by evaluating evidence to make a decision. Critical thinking involves critique and emotion involves the state of feeling (Brecher 2014).

5.3 Sampling Agent-Based Technologies That Resemble Human Domain Elements

For this section of the report, the study surveyed 72 instances of academic ABM frameworks (see Appendix A). Models and research, using these frameworks, were examined for their resemblance to the described Human Doman elements; that is, whether each model exhibits some amount of utility, such as the possibility of being an external reference to research, for the purpose of developing future Army- and tactically specific agent-based models.

In general, the scope of this survey is limited to academic-level research and, where possible, is limited to discussion of models with possible tactical relevance. While there is some promising research, the majority of the available ABM research is at a basic research level of maturity (Brecher 2014).

5.3.1 Social Technologies

In this section, 3 models—GROWlab (Geographical Research on War Laboratory), RebeLand, and AfriLand—provide the reader with an indication of the maturity of current social Human Domain research. Project Albert and PAX are other research projects that seek socially relevant capabilities (Koehler et al. 2004; Tan 2004; Schwarz 2004, 2005; Johnson et al. 2009).

GROWlab is a suite that models countries at the regional and national levels. Attributes of the model include country borders, state and local institutions, and ethnic groups within countries. However, the primary emphasis is to modelling conflict within and between countries and modelling social elements at a high level of fidelity. A particularly useful aspect of GROWlab is that a number of databases on the modeled countries are available. As such, these resources could be useful for Army researchers.

GROWlab's database includes data on 160 countries, covering dates between 1946 and 2013 (Vogt et al. 2015). Historically, research enabled by GROWlab has modeled conflicts between states or national-level conflict within a state, such as a civil war. A user interface included with GROWlab helps researchers visualize subsets of data and contains information such as settlement patterns. This interface allows the researcher to identify traditional ethnic regions, the amount of access a group has to executive power, the population, the Gross Domestic Product, and/or terrain data. The user interface also allows the researcher to download queried datasets.

By using the available data, GROWlab researchers have been able to find points of conflict. For example, in Bangladesh, 4 ethnic groups have divided political power. Database records helped researchers to discover that Bengali Muslims were the politically dominant ethic group and that the Bengali Hindus, Biharis, and Tribal Buddhists were being politically discriminated.

Another agent-based modeling framework used to model conflict, MASON, has been developed into a model called RebeLand (Cioffi-Revilla and Rouleau 2009a). RebeLand models a fictitious island nation consisting of a national government and 3 provinces. Each province had a state (provincial) government, population, and resources. Researchers used this model to examine political stability to measure the impact of different policies. Political stability is the ability of a political system to withstand changes given a range of stress, such as social, economic, or environmental, and RebeLand acted as a model to help researchers better understand conditions that contribute to stability.

Using their experience with RebeLand, the same team developed another model on top of MASON called AfriLand, which modelled the government and society of 10 eastern African countries: Sudan, Ethiopia, Somalia, Djibouti, Eritrea, Rwanda, Burundi, Kenya, Tanzania, and Uganda (Cioffi-Revilla and Rouleau 2009b). The model helped identify conflict within and between the countries, especially through examining the effects of transborder and transnational issues, such as refugee migration and societal stress. Concepts demonstrated with RebeLand, such as the interaction of politics, society, government, and associated issues, were reused in the AfriLand model.

Using the empirical relevance framework described earlier, all 3 models are assessed at Level 0 maturity (i.e., representing a caricature of reality) in terms of their applicability to tactical modeling. In the case of GROWlab, the model provides between a Level 0 and Level 1 representation at the strategic or national level. GROWlab provides a high level of detail for ethnic populations at the country and region levels but also embodies lower-level detail (e.g., city, town, and village). Comparatively, the other 2 models, RebeLand and AfriLand, demonstrate a representation of both national and local governments; however, it is unclear whether the model authors used real-world data observations to calibrate social representations and interactions within the model.

5.3.2 Cultural Technologies

Several agent-based models exhibit cultural attributes: VECTOR, Hispanic Population Model, Insurgency Dynamics, and SWARM.

VECTOR is a project that implements cultural knowledge and interaction for training within a game-type interactive environment. VECTOR uses cognitive agents to create an immersive cultural-awareness-training environment for Soldiers (Bell 2005). The game uses agents to model a number of actions that include the behaviors of nonplayer characters within the population, realistic interactions of virtual actors with the trainee, and the demonstration of emotion in virtual actors.

Another model, Hispanic Population Model, examines Hispanic acculturation within the United States (Wallis et al. 2004). The model uses the AnyLogic ABM framework to examine both individual agent behavior and that of the environment, especially people moving in and out of modeled neighborhoods. The model included individual person variables for aging, income, education decisions, and the choice of whether and when to have children. At the macrolevel, Hispanic Population Model models aggregate behaviors, such as the decision to live in a dominantly Hispanic area.

The Insurgency Dynamics process model, published by AnyLogic, divides a population into 4 groups: government supporters, dissidents, insurgents, and removed insurgents. Both dissidents and insurgents interact with government supporters, and various amounts of the population are stochastically swayed toward one group or the other. The government seeks to minimize the size of the insurgents group, and the strength of the effort depends on resources and the size of the insurgents group.

A fourth model uses the SWARM ABM framework (Allan 2010) to simulate ethnic mobilization, based on migrations in the former Yugoslavia (Srbljinovic et al. 2003). In this model, agents were composed of 3 attributes: ethnic membership, affinity to their ethnicity, and social network. This research demonstrates that the frequency of messages (e.g., stay at the current location, move to a new location) had the effect of increasing the speed of mobilization, while increasing neutral appeals slowed mobilization down. Regardless of this finding, mobilization increased if the agent had a social network (alternative findings include those by Hamill and Gilbert 2008, 2010). Overall, the researchers found that multiple stable states could exist and outcomes often depend on the initialization values of agents' mobilization intensity and number of social-network connections.

Using the empirical relevance framework, all 3 models are assessed between Level 0 and Level 1 maturity (i.e., between a representation of a caricature of reality and a qualitative representation at a macrolevel) in terms of their applicability to tactical modeling.

5.3.3 Physical Technologies

Most of the models of physical elements contain spatial attributes and range from 2-D grids to 3-D GIS spaces. Despite the fact that the majority of the following descriptions specify the use of GIS capabilities, many researchers prefer to use simple 2-D spaces in their models for convenience and reduced complexity (Burtsev and Korotayev 2004; Andrade 2010; Johnston 2013). The models discussed in the following are 2 versions of GAMA, Acequia-based Agriculture, RebeLand, and the Hydrogen Economy model.

GAMA is an ABM framework that enables use of GIS data within models (Taillandier et al. 2012). GAMA handles the geometries by utilizing traditional shapefiles, raster files, or mesh files. These types of files enable GAMA to import attributes such as geography, hydrology, and other factors, such as road networks.

Some research has investigated using agent-based models to evaluate policies for improving urban mobility (Bathe and Frewer 2008; Fosset et al. 2016). This work used the GAMA framework to create a virtual representation of Grenoble, France. The model replicated buildings, businesses, streets, traffic, and populations to determine the effects of policies on pollution in the city. Shops and businesses were considered resources, with populations moving from homes to work and/or shopping.

Other research has used GAMA to study the social, economic, and ecological impact of water management in the Adour-Garonne Basin, France (Grignard et al. 2013). This particular model simulated the physical elements of the geography, hydrology, urbanization, and resources within the greater basin area.

Another model, Acequia-based Agriculture, has investigated situations involving water management in New Mexico (Wise and Crooks 2012). GIS data for the county of Taos, New Mexico, and its surrounding area was imported from the US Geological Survey's EarthExplorer into an agent-based model using the MASON framework. Information included terrain elevation change, shapefiles, and land-use data. Land use included data describing urbanization and agriculture areas. The overall model replicated real-world conditions of terrain and hydrology (i.e., rivers, acequilas) and decisions made by individual landowners. The result of the model is a realistic socio-physical system simulating water-supply use, resulting agricultural consequences, and the impact to the surrounding communities.

Similarly, the previously discussed RebeLand model incorporated physical terrain features, including topology and vegetation land cover. Moreover, a simple weather system simulated climate variability, the impact of droughts, and other natural stressor events. The model also included natural resources distributed throughout the terrain, such as oil, diamonds, and gold.

Another model is the Hydrogen Economy Model, which models highways and local road information of the Los Angeles, California, metropolitan area (Mahalik et al. 2007). In this model, a 2-D grid and cell representation is used to model the world, but a GIS-layout of roads informs which cells are “road” cells. Two types of agents are included in the model: drivers and investors. Driver agents move their cars between demographically assigned home neighborhoods and job sites. Drivers have a variety of characteristics, such as income levels, environmental concerns, risk aversion, and car type preferences (e.g., conventional vs. hydrogen). Investor agents build, own, and operate hydrogen fuel stations based on the investor’s estimates for potential profit at available locations. Researchers used the model to investigate practical and logistical questions concerning the plausibility of hydrogen-based vehicles.

Using the Empirical Relevance Framework, all 5 models are assessed between Level 0 and Level 2 maturity (i.e., between a representation of a caricature of reality and a quantitative representation at a macrolevel, in terms of physical elements) in terms of application to tactical modeling. The distributions of these models illustrate the range of specificity models may use to affect simulations. Current research capabilities, if selected, can model some physical features (e.g., using GIS-annotated data, modeled weather systems) with sufficient accuracy for use by tactical military planners.

5.3.4 Informational Technologies

The Human Domain informational element specifies 3 subelements: the transmission, the message, and the audience. However, in this survey, the authors could not find any models that explicitly examined the modality of communication. Each model reviewed in the following—Janus, ACT-R, and Geo-Game—exhibits some form of communication (i.e., interaction); one of the premises of ABM is that agents interact with each other and their environment. The general agent-based interactive process partially represents the transmission and audience subelements, such as some agents being aware of or receptive to information communicated by other agents.

The Janus agent-based model, simulating carpooling situations, provides an example of how informational subelements may be incorporated (Hussain et al.

2015). Agents must belong to the same social group (e.g., communication channel) to send and receive communications (Gaud et al. 2008). Agent roles are the basis for all model interactions, and each agent has a queue for sending and receiving messages. Messages are delivered according to recipient roles.

Similarly, in the ACT-R model, agents who are in the same network pass information between themselves. However, the means of communication is not included in the model. The Geo-Game model exchanges information through individual "chats" (Reitter and Lebiere 2011). Similarly, this model does not include social-media mechanisms.

Using the Empirical Relevance Framework, these models are assessed at a Level 0 maturity (i.e., a caricature representation of reality), in terms of application to tactical modeling. At a tactical level, the means of transmission is essential to planners. Information operation messages can fail because of the limitations of the modality chosen.

5.3.5 Psychological Technologies

Of all the academic-research models the study identified, 2 stood out in their capability to represent psychological subelements. ACT-R and SOAR implement various capabilities and maturities of 4 subelements: cognition, judgment, emotion, and critical thinking. Each model represents these subelements differently, particularly with respect to emotion, but both approaches exhibit positive attributes.

ACT-R is a framework, based on the theory of rational analysis, used in the development of cognitive models capable of predicting and explaining human behavior. It models human cognition as a series of modules interacting with the external environment. The ACT-R architecture is composed of a visual object recognition module, a module for controlling extremities, a declarative module for retrieving information from memory, and a goal module that tracks goals and intentions (Anderson et al. 2004). Each module has an associated buffer that stores information. A central production system coordinates information placed in the buffers. It also processes buffer information, recognizing patterns and triggering module-specific rules that ultimately result in actions. Depending on the application, researchers may add additional modules as long as the same basic architecture is used.

Research for the Georgia Tech Aegis Simulation Program successfully used ACT-R to model cognition, judgment, and critical thinking (Fu et al. 2006). This project evaluated a visual display to provide mission-critical information to Anti-Air Warfare Coordinators. The task involved acquiring information such as aircraft location and speed to classify aircraft in a timely manner. ACT-R modeled

2 cognitive processes: first, the conversion of visual inputs from the display screen to the coordinator's memory, and second, the discernment and classification of aircraft type. The results of the modeling closely mirrored human times.

The ACT-R framework does not have a built-in module dealing with emotions. However, researchers have proposed different means to address this issue; for example, Roman Belavkin (2002) suggested an implementation using attributes of the conflict resolution component to realize emotions. Although these suggestions are not implemented in the framework, they demonstrate a means to deal with emotions within the model.

SOAR differs from ACT-R in fundamental ways, using multiple memory and processing modules. For example, Procedural, Semantic, and Episodic memories are used for short-term memory. Another difference is in handling conflict resolution; ACT-R evaluates current information with matching rules to select actions, whereas SOAR implements all matched rules in parallel and deliberates on the selection and application of operators. SOAR operators are procedures with preconditions; in other words, a condition must be true to activate an operator, and if it is so, the procedure will run.

SOAR expresses Human Domain psychological subelements within its decision cycle. During input, the model acquires data from the environment. In the "propose" phase, critical thinking is realized by applying rules to acquired data. The next phase, "decide", applies judgment in making decisions on which rule to implement. Once SOAR makes a decision, rules describing how to apply the operator are activated.

As with ACT-R, SOAR does not have a built-in module for emotions. However, similarly to ACT-R, there has been research suggesting such modules. For example, one module implemented within SOAR integrated emotions into the cognitive model using appraisals. Appraisal theory suggests that emotions result from the relationship between goals and situations, along specific dimensions (Marinier et al. 2008).

Numerous research has used the SOAR framework since the 1990s (Soar-Related Research 2016). The TacAir-Soar agent was one such project that developed a rule system for fixed-wing aircraft (Jones et al. 1999; 2009). Project-developed innovations included reasoning capabilities, integration with a simulated environment, a representation of human-like coordination and communication, and situational understanding to drive agent reasoning. The result was a system capable of executing most airborne missions that the US military flies in fixed-wing aircraft. This research accomplishes these objectives by integrating a variety of capabilities, including reasoning about interacting goals, reacting to rapid changes in real time, communicating and coordinating with other agents and humans, maintaining situational awareness, and accepting new orders during flight. Because of TacAir-SOAR's success, it can model and implement appropriate tactical behavior for a broad variety of such missions routinely used by the US Navy, Air Force, and Marines; the UK Royal Air Force; and opponent forces in full-scale exercises.

According to the Empirical Relevance Framework, the ACT-R model operates at approximately Level 2 maturity (i.e., a quantitative representation at a macrolevel, in terms of psychological elements) in terms of application to tactical modeling. However, the SOAR model, given the proper adaption to the applied domain, can likely operate between Level 2 and Level 3 maturity (i.e., between a quantitative representation at a macrolevel and a quantitative representation at a microlevel, in terms of psychological elements). These models illustrate the ability to model human cognition through a number of scenarios, but both models also have similar weaknesses in modeling emotion.

5.4 Sampling and Analysis of Agent-Based Research

While the prior section addressed existing academic agent-based models, this section evaluates a selected sample of publically available agent-based research. Papers submitted to the Computational Social Science Society of the Americas (CSSSA) serve as a sample from which to extrapolate the nature of public research applicable to Human Domain elements. The study samples 54 papers submitted to and published by the last 3 CSSSA conferences, held in 2012, 2013, and 2015. The same level of relevance to Human Domain scale, outlined and used in the prior section, is once again used to provide the reader with an indication of the maturity and breadth of current research.

The following illustration is a heat map of the categorized research. The surveyed research works are enumerated in Appendix B. Their identification (ID) numbers correspond to the numbers used in Fig. 28. Each of the 54 papers sampled are listed, with recent conference papers starting at line one. One hundred and eighteen unique authors and coauthors contributed to these articles and approximately 15% of those authors contributed to more than one paper over those 3 submission years. Light-gray cells indicate no discussion of the identified Human Domain element and/or subelements. A mid-gray color indicates a Level 2 estimate; that is, there is some discussion of the designated Human Domain attribute and the paper could be used in future research to justify a research direction. A darker gray indicates the paper had enough assessed maturity that the research could be a starting point for future Army applications. None of the papers appeared to warrant maturity level ratings of 4 or 5, which would be research appropriate for various degrees of off-the-shelf integration into tactical Army wargaming application.

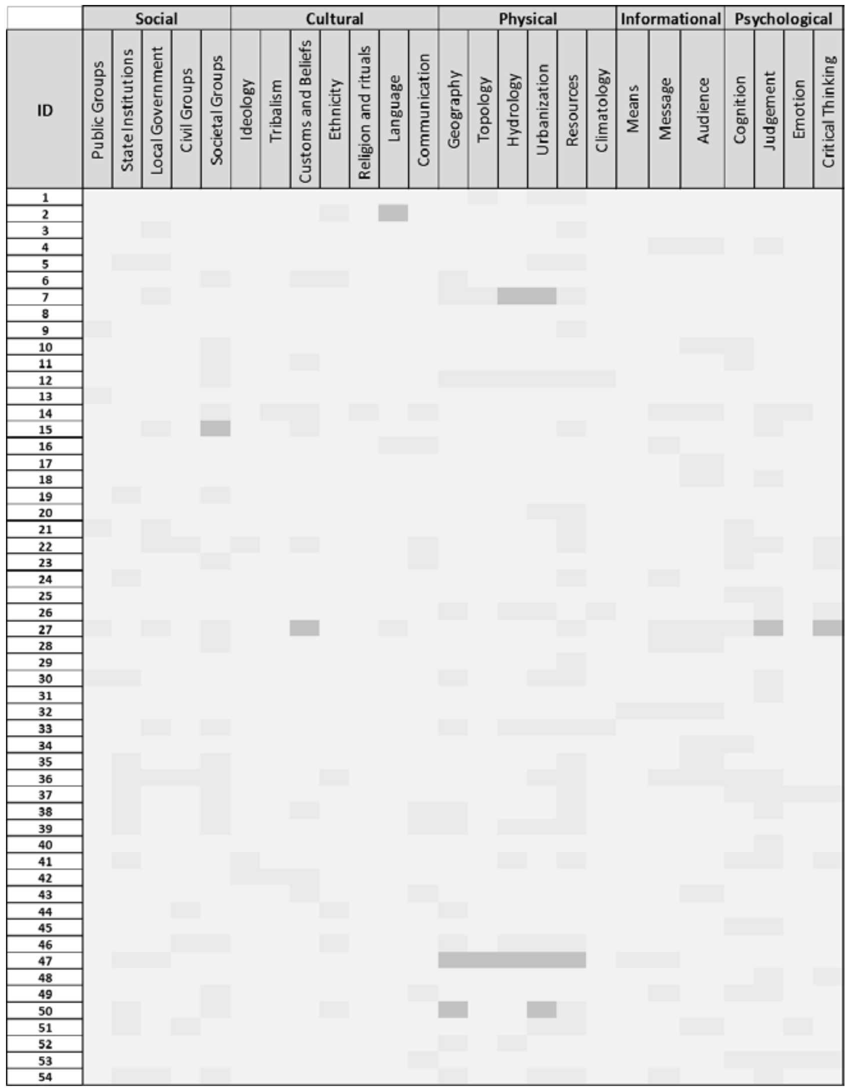

Fig. 28 A heat map identifying whether papers submitted to CSSSA conferences (2012, 2013, and 2015) exhibit characteristics identified by the Human Domain. Dark-gray cells indicate research that the Army could potentially use to develop Army-specific tactical ABM capabilities.

The objective of this assessment is to provide a holistic sense of the nature and maturity of research within computational social science community. It may be possible that the assessed value of a specific paper is found incorrect upon review. In addition, it should be remembered that this distribution of research is a sample; other conference proceedings—such as those provided by Behavior Representation in Modeling & Simulation, the Journal of Artificial Societies and Social

Simulation, and the Journal of Complex Systems—are likely to have different distributions of the nature of presented research and published works.

After categorizing each paper, the authors evaluated results holistically in 2 ways. The first type of evaluation involved simply calculating the numeric sum of each row. The goal was to find research that demonstrated a broad spectrum of Human Domain influences, and this evaluation produced several interesting results. First, the research with the highest scores correlated with both maturity and existence of contextually larger simulation projects. For example, the top IDs were no. 27 and 47. These 2 papers corresponded respectively to 1) Deborah Duong's (2013) paper regarding a specific capability used in the Army's IW TWG analysis and 2) the paper by Latek, Rizi, Crooks, and Fraser (2012), which identifies an agent-based capability to assist with finding border crossings and determining the possibility of detection, sponsored by EADS North America.

Research with the highest scores correlated to research that was more comprehensive than other peer research. For example, Michel and Megerdoomian (2015) demonstrated population-physiological interactions (e.g., exhibiting characteristics of fear, disregard) in the context of environmental dangers, specifically Ebola outbreaks. Alternatively, McCaskill (2013; listed in Appendix B) investigated intervention strategies for coordinating military and nongovernmental-organization activities. This paper diverged from common practice within the computational social-science community—namely, the practice of keeping the model as simple as possible to emphasize and demonstrate the intended phenomena. However, in McCaskill's paper, the authors found that, as additional context was included in the author's research, the developed model became more compelling. The results of this paper suggest that it is likely necessary to keep models simple while developing the "science of the phenomena and/or model", but it is reasonable to associate additional, contextually relevant variables thereafter, during 6.2-Applied Research or 6.3-Advanced Technology Development.

The second evaluation strategy computed the sum of each column. The 3 most common Human Domain subelements referenced in the sampled research were Physical (Resources), Social (Societal Groups), and Psychological (Judgement). Coming from the perspective of using an ABM approach, this result makes sense. In their simplest form, agent-based models are the combination of agents interacting with each other and their designated environment. Thus, researchers often use resources as a proxy representation of the environment. Societal groups often become the lowest common denominator of interacting agents within models. Finally, agents within the model enact judgment by making decisions, regardless of whether the decision possibility (i.e., stochastics) was determined a priori or learned during each simulation.

Under this evaluation strategy, the aggregate identification and use of Human Domain subelements followed a power-law distribution (Cioffi-Revilla and O'Brien 2007, p. 29). Some subelements are referenced several times more than the least-referenced subelements. In contrast, the broad Human Domain elements are referenced a proportionally similar number of times. The proportional distribution was computed by taking the sum of each column within an element and dividing it by the number of included columns, thus representing a normalized number of references. Surprisingly, the Cultural Human Domain element and subelements (e.g., ideology, tribalism, religion and rituals, and language) were the least represented and researched area.

5.5 Sampling of Foreign Agent-Based Research

This section provides a comparison between agent-based models published in the United States and those published by organizations in China and Russia, to illustrate the nature of comparable research in other countries. As in the previous section, the goal is not to provide an exhaustive representation but to provide an overview of ongoing research. These samples emphasize military-relevant or other topical agent-based research and are organized according to their originating cities and institutions.

5.5.1 Chinese Agent-Based Research

The 28 research papers sampled originated from 24 institutions in 7 cities throughout the country (Fig. 29). Sampled papers are identified in Fig. 30 and are grouped and sorted by the city, the institution, and name of the paper. Duplicate titles thus occur when authors from multiple institutions collaborated on the paper (Kai-jia et al. 2012; Jiangl 2015).

Fig. 29 Seven cities throughout China, identified numerically on this map, represent the locations of published agent-based research.

Beijing, China (Fig. 29, Location 1)

ACADEMY OF MILITARY MEDICAL SCIENCES
"A framework of multilayer social networks for communication behavior with agent-based modeling"

BEIJING INSTITUTE OF ELECTRONIC SYSTEM ENGINEERING
"Study on MAS-based Modeling and Simulation of Land Combat"

BEIJING UNIVERSITY
"On Crowd Psychology Behavior Simulation and Security"

CHINA AGRICULTURAL UNIVERSITY
"The Agent-based Architecture and Simulation of Intelligence Traffic"

CHINA DEFENSE SCIENCE TECHNOLOGY INFORMATION CENTER
"Study on MAS-based Modeling and Simulation of Land Combat"

Fig. 30 An enumeration of military-relevant or other topical agent-based research produced by Chinese organizations. Locations, organizations, and names of papers are identified.

Beijing, China (Fig. 29, Location 1 cont.)

CHINESE ACADEMY OF SCIENCES
"Agent-Based Modeling of Netizen Groups in Chinese Internet Events"

COMMUNICATION INSTITUTE OF CESEC
"A Mobile Agent-Based Network Management Architecture and Simulation System for Special-Operational Radio Communications Networks"

INSTITUTE OF SOFTWARE
"The Agent-based Architecture and Simulation of Intelligence Traffic"

NATIONAL DEFENSE UNIVERSITY
"Research on Military Simulation System based on Multi-Agent"
"Study on Some Key Issues about Agent-Based Modeling in War Complex System"
"Study on Agent-based Comprehensive-domain War Universe"
"Research and Implementation of the Third Party Intelligence Agent's Strategy Decision-Making Behavior Model"

PLA UNIVERSITY OF SCIENCE & TECHNOLOGY
"Evaluating Effectiveness of Information Sharing via Combat Simulation Based on Agent"
"Lanchester combat model in conditions of modernized warfare"

RENMIN UNIVERSITY
"Analysis and Simulation on Mass Psychology by CAS Theory" [includes models of policy research]

Nanjing, China (Fig. 29, Location 2)

NANJING ARMY COMMAND COLLEGE
"Model and Method for A Multi-Agent-based Ammunition Consumption Calculating"
"Research on Agent-based Modeling and Simulation of Military Counter System"
"Personality and propagation model of psychological war agent"
"Dynamic Model Research on Ammunition Demand in Combination of Firepower Blow"

NAVY TRAINING EQUIPMENT INSTITUTE
"Agent-based Modeling and Controlling Strategy in Generation of Virtual Battlefield Scene"

PLA UNIVERSITY OF SCIENCE AND TECHNOLOGY
"Study on Combat Agent Model"

SOUTHEAST UNIVERSITY
"Agent-based Modeling and Controlling Strategy in Generation of Virtual Battlefield Scene"

Fig. 30 An enumeration of military-relevant or other topical agent-based research produced by Chinese organizations. Locations, organizations, and names of papers are identified (continued).

Wuhan, China (Fig. 29, Location 3)

COMMUNICATION COMMAND ACADEMY
"Dynamic Model Research on Ammunition Demand in Combination of Firepower Blow"
"Study on MAS-based Modeling and Simulation of Land Combat"

NAVAL UNIVERSITY OF ENGINEERING
"A Mobile Agent-Based Network Management Architecture and Simulation System for Special-Operational Radio Communications Networks"

SECOND ARTILLERY COMMAND COLLEGE
"Dynamic Model Research on Ammunition Demand in Combination of Firepower Blow"

Bengbu, China (Fig. 29, Location 4)

BENGBU NAVAL PETTY OFFICER ACADEMY
"Recognition-Primed Decision-Making Model Based on Multi-Agent"

BENGBU TANK INSTITUTE
"The Research on Modeling and Simulation of Warfare Decision-Making Behavior"
"Research on Agent-based Modeling and Simulation of Military Counter System"

Changsha, China (Fig. 29, Location 5)

COLLEGE OF ASTRONAUTICS AND MATERIAL ENGINEERING
"Study on Complex Adaptive System and Agent-Based Modeling & Simulation"

NATIONAL UNIVERSITY OF DEFENSE TECHNOLOGY
"A framework of multilayer social networks for communication behavior with agent-based modeling"
"Research on Effectiveness Evaluation of Psychological Operations Based on Multiple-agent Modeling and Simulation Method"
"Research on modeling method of complicated information system based multiple intelligence agents"
"A Multi-Thread Implementation Method of BDI Agent"

Hefei, China (Fig. 29, Location 6)

ARTILLERY ACADEME OF PLA
"Law of Dynamic Consumption for Artillery Ammunition"

Xi'an, China (Fig. 29, Location 7)

XI'AN RESEARCH INSTITUTE OF HI-TECH
"Research on Behavior Modeling Method of Agent-Based CGF" [includes models of brigade, battalion, and operational units]

Fig. 30 An enumeration of military-relevant or other topical agent-based research produced by Chinese organizations. Locations, organizations, and names of papers are identified (continued).

5.5.2 Russian Agent-Based Research

The 8 research papers sampled represent 6 institutions in 3 cities across Russia (Fig. 31). The papers are organized in a similar manner to those from China and are identified in Fig. 32 (Kotenko 2010; Kotenko et al. 2006; Makarov and Bakhtizin 2010).

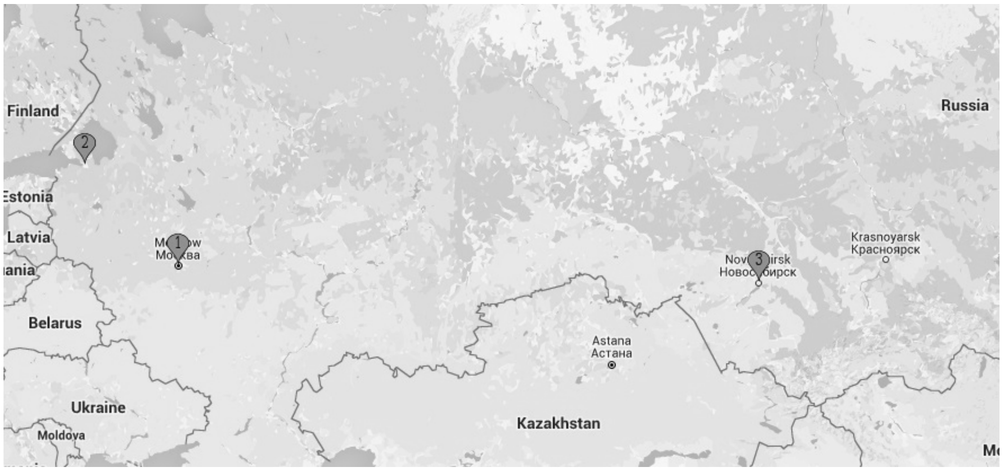

Fig. 31 Three cities throughout Russia, identified numerically on this map, represent the locations of published agent-based research.

Moscow, Russia (Fig. 30, Location 1)

CENTRAL ECONOMICS AND MATHEMATICS INSTITUTE OF RUSSIAN ACADEMY OF SCIENCES

"Agent-based model for simulation of terrorism in Russia's Caucasus"

RUSSIAN ACADEMY OF SCIENCES

"An Evolutionary Agent-Based Model of Pre-State Warfare Patterns Cross-Cultural Tests"

St. Petersburg, Russia (Fig. 30, Location 2)

ITMO UNIVERSITY

"Multiscale agent-based simulation in large city areas: emergency evacuation use case"

"The Multi-Agent Simulation-Based Framework for Optimization of Detectors Layout in Public Crowded Places"

ST. PETERSBURG INSTITUTE FOR INFORMATICS AND AUTOMATION OF RUSSIAN ACADEMY OF SCIENCES

"Agent-based modelling and simulation of network cyber-attacks and cooperative defence mechanisms"

Fig. 32 An enumeration of military-relevant or other topical agent-based research produced by Russian organizations. Locations, organizations, and names of papers are identified.

St. Petersburg, Russia (Fig. 30, Location 2 cont.)
“Agent-based modeling and simulation of malefactors’ attacks against computer networks”
“Agent-Based Modeling and Simulation of Cyber-Warfare Between Malefactors and Security Agents in Internet”

Novosibirsk, Russia (Fig. 30, Location 3)
ACAD. LAVRENTYEVA
“Spatial Aspects of Agent-Based Modeling of Large Economy”
NOVOSIBIRSK STATE UNIVERSITY
“Spatial Aspects of Agent-Based Modeling of Large Economy”

Fig. 32 An enumeration of military-relevant or other topical agent-based research produced by Russian organizations. Locations, organizations, and names of papers are identified (continued).

5.6 Summary

This section has summarized existing agent-based tools and capabilities. It then contextualized published agent-based research in terms of Human Domain elements and the maturity level of the research and/or models, including a brief enumeration of foreign agent-based research. In spite of the breadth of published agent-based research and models, only a few capabilities are immediately applicable to tactical wargaming. For agent-based capabilities to become tactically useful to the Army, additional research and development is needed, emphasizing maturation of existing research to address tactical wargaming needs. The next section lays out a plan for such research.

6. Plan for Research, Development, Technology, and Training

This report has evaluated the capabilities of agent-based analytics and game theory with the goal to identify potential investment areas for Army S&T targeted for research and development relative to automated and semiautomated analysis. For its purposes, the authors examined ABM as a means to improve wargaming rigor and minimize decision-making risk in the Human Domain, specifically through its application to tactical battalion-, brigade-, and division-level wargaming. A detailed study found a wide breath and combination of agent-based research and accomplishments. Based upon those findings, this report concludes with several recommendations, along with a discussion of the limitation of the technologies, a comparison to peer technologies and an Army-relevant technological path forward.

The desire behind using and applying technological capabilities, such as ABM in tactical wargaming situations, is to reduce the friction and cost of conflict with respect to the broader population. MG Flynn said, “Simply stated, the lesson of the last decade is that failing to understand the human dimension of conflict is too costly in lives, resources, and political will for the Nation to bear” (Flynn et al. 2012). Advanced technology itself, such as artificial intelligence, ABM, and game theoretic techniques, does not provide solutions to human conflict. Similarly, unwitting kinetic actions may be necessary but are not sufficient to resolve conflicts and fulfill political objectives: “The lesson is that while there are military victories there is never a military ‘solution.’ There’s only military action that creates space for economic and political life” (Stewart 2013).

After World War I, TE Lawrence profoundly stated, “War upon rebellion was messy and slow, like eating soup with a knife,” an appropriate analogy to the Army’s current wargaming process as applied to the civilian population. The Army is a powerful instrument of political will, built to withstand and defeat enemy forces, but it holistically plays an additional role of laying foundations for future economic, political, and social stability and peace. This study has evaluated agent-based technologies within the context of Army wargaming, knowing that while the plan of conflict itself changes the moment it begins, there is also conscious time set aside to evaluate decisions, which influence the Human Domain beyond kinetic actions. In many instances of the Human Domain, “tribalism is underneath everything; every glance, every knowing look, every payment, every invitation, everything that happens is linked to tribal connections” (Stewart 2013). Human populations—especially their interactive social, cultural, and tribal elements—are features of the social environment just as terrain is of the physical environment, and both aspects are vital to military, economic, and political objectives.

6.1 Recommendations

This report proposes 4 recommendations: 1) begin researching and developing an Army-centric ABM capability, 2) form a stateside repository, 3) implement an ABM capability as a multilayered, distributed application, and 4) provide applicable training to ensure appropriate and knowledgeable proficiency. A combination of each of the aforementioned is essential to the success of the Army mission. Furthermore, the risk of not having a tactical ABM wargaming capability in the future would be worse than the status quo.

6.1.1 Research and Develop an Army-Centric Agent-Based Modeling Capability

The first recommendation is that the Army S&T community begins researching and developing Army-centric agent-based models. Four elements make up the basic and applied research recommendations: research and development of resources that model tactical Human Domain attributes, research and development of automated reasoning processes that support rigorous analysis, research and development of a cognitive-social framework, and evaluation of resources and models in terms of a model maturity framework. This report identifies short-, medium-, and long-term research goals for each of the 4 elements, and describes each step in terms of usefulness to the Army.

Army Special Forces Command has identified interrelated attributes necessary to model the Human Domain, namely social, cultural, physical, informational, and psychological elements. Numerous attributes of the Human Domain have been studied and documented within the social science field and generally take the form of research papers and reports and occasionally as proof-of-concept examples. This report recommends adopting and slightly adjusting the proposed Human Domain Framework, integrating existing social science research, and addressing military-specific gaps in that research. Game theoretic attributes of dynamic culture and low-rationality actors are likely to play a complementary modeling role, and the study recommends research, which incorporates these conceptual notions within a traditional application of agent-based models. Finally, the study recommends basic research investigating problems related to the connections and interactions between Human-Domain elements.

While agent-based technologies are at the core of the study's recommendation, a complementary need exits for semiautomated reasoning processes to support rigorous analysis. Traditional notions of reasoning include concepts of deduction, induction, and abduction; the authors see a variety of situations where appropriate development of these concepts facilitates successful application of tactical ABM.

A narrative capability—research and development of a capability that analyzes model output and translates it into a narrative textual format with descriptions and interpretations—is one such example. The study recommends research identifying points at which human interaction affects operation of models; decision (human in the loop), veto (human on the loop), and analysis (human inside the loop) are examples of such interaction modes. Moreover, while ABM exhibits emergent properties, research of automated deductive capabilities that support translation and implementation of courses of action is useful. In addition, development of automated monitoring, model-adjustment, and alerting capabilities are appropriate (Sudit et al. 2013).

ABM and additional supporting technologies have the potential to introduce a third-generation (i.e., cognitive) wargaming capability to the Army, creating a positive overmatch decision-making capability. As a means to enable this ability, this study recommends researching and developing an understanding of the psychological dimension of agent behavior to model microlevel interactions through cognitive and interactive social relations. Subsequently, it also recommends investigating any resulting macrolevel properties of collections of cognitive-social agents interacting with their environments. Social networks, traditional and modern tribal groups, and local governments, each with their respective properties, are a possible means of measuring whether such a capability is sufficiently mature. Finally, the study recommends researching, developing, and evaluating course-of-action analysis using cognitive-social agents in terms of military and political objectives.

Verification and validation of models, actors, and resources will likely be the most difficult aspect of developing an Army tactical agent-based capability. The study recommends that the Army consider adopting a standardized framework, such as the one originally proposed by doctors Rob Axtell and Joshua Epstein, to ensure stakeholders communicate with the same language; this is not a standardized data schema or ontology but rather an evaluative framework (Egeth et al. 2014). The Axtell–Epstein framework identifies 4 levels of maturity: Level 0 as a caricature of reality, Level 1 as a qualitative representation of macrostructures, Level 2 as quantitative representation of macrostructures, and Level 3 as a quantitative representation of microstructures. Model maturity helps end-users identify the nature of model results. Moreover, the study recommends the Army delay standardization of model interfaces—for example, using specified data schemas or ontologies—until individual models and resources reach Level 3 maturity.

6.1.2 Form a Stateside Repository

The second recommendation is to form and maintain a stateside repository of worldwide applicable models, agents, and resources; that is, a so-called Army

Wargaming Intelligence Center. The authors base this recommendation on the "Request for Support" functionality that the Joint Improvised Threat Defeat Agency's (JIEDDO) Counter-IED Operations/Intelligence Center (COIC) supported with its "Attack the Network" operations (Del Vecchio et al. 2010). In particular, a system and set of processes and personnel who support timely (e.g., 6 h, 24 h, 14 days) requests for information while interacting with liaisons representing a whole-of-government to coordinate wargamed courses of action. Moreover, it recommends the Army use the proposed Stateside Repository as a wargaming center to ensure consistency of interaction between rotating deployments of tactical units and local populations. The stateside center would become a repository for current and historical wargaming resources. Several existing capabilities exhibit some tactical-level capabilities to Army should investigate further (e.g., IW TWG, SEAS/RWISE; see Section 5).

6.1.3 Implement an ABM Capability as a Multilayered Distributed Application

The third recommendation is to implement the Army agent-based capability as a multi-layered and distributed application. The study recommends the Army require the user-interface implementation to be a web-based application, compatible with the Distributed Common Ground System–Army (DCGS–A) Program of Record. However, in light of possible network disconnections at the tactical level, the web-based application would need to run as a standalone hybrid web-application on a client machine. If broader network access is available, distributed, parallel processing, and/or cluster resources may be available for additional combinatorial scenario processing. Ideally, the agent-based capability would be sharable vertically and horizontally throughout the command and support structure, allowing individual users to receive, share, and maintain their own specific settings and model configurations. Finally, the study recommends models are version-controlled through the proposed stateside repository, using a distributed version control system such as GIT.

6.1.4 Provide Applicable Training to Ensure Appropriate and Knowledgeable Proficiency

The fourth recommendation is to incorporate applied topics of culture, tribes, complex adaptive systems, game theory, and applied statistics into specialized education and training curriculums, such as those provided at the Command and General Staff College (CGSC) and Warrant Officer training at the Combined Arms Center. The study also recommends the Army introduce a semiregular certification requirement encompassing basic essentials, applied methodology, and application of agent-based capabilities during wargaming.

6.2 Potential and Limitations

While the recommendation is to research and develop an Army-centric ABM capability, this is a nontrivial task. To research, develop, deploy, and maintain any agent-based capability will be a daunting task. The Army will need to devote significant person-hours to perform leading research and development, adequate verification and validation, subsequent model creation, and resource revisions. Similarly, a nontrivial amount of money, appropriated throughout the range of 6.1-Basic Research to 6.7-Operational System Development money, and people serving in both stateside positions and training will be necessary (Fossum et al. 2000). However, little or no Army doctrine change is necessary. In general, an agent-based modeling can improve intelligence analysis rigor but the study recommends connecting the standalone capability to a "check and balance" process; without the combination of the process and the technology, the authors foresee the possible misuse or misapplication of the modeling capability in the future, resulting in an increase in tactical risk.

In the immediate and near future, an ABM will not be able to forecast an exact future of tactical situations or precise Human Domain outcomes. However, an agent-based capability can help minimize risk by improving contextual awareness, communicating informed consequences of tactical decisions, and improving the study and training of warfare. In general, an agent-based capability requires a different type of thinking than structural problem solving. ABM is not an optimal or precision tool; rather, ABM is a robust tool that communicates a range of possibilities, including associated warning indicators with estimated possibilities of occurrence. The emphasis of the capability is on understanding and modeling the situation within the larger context of human interactions, and then working within the available Human Domain population.

Initially, ABM was developed in the field of mathematics. However, because the mathematics community deemed the modeling technique too inexact, it migrated to economics where it was discovered to be more rigorous than other alternative techniques. Discussion with members in the computational social-science discipline has indicated that some disagreement exists within the academic community as to whether heuristic results produced by agent-based models and their rules are as good and justifiable as the precise sets and results of formal mathematics, such as differential equations (Pramukkul et al. 2013). Because of the need to address the value of these results, there is potential for a new academic discipline of computational social science to emerge in the future, similar to emergence of the computer science field.

If the Army decides it does not want to use an agent-based capability, this report recommends at least being prepared for an adversary to use it. The authors see agent-based capabilities as modeling the physics of social science; as an analogy, an eventual agent-oriented “bomb” capability could be possible (West 2015). ABM will likely be a military capability of the future; both state and nonstate actors could weaponize it. In the commercial domain, agent-based modeling is beginning to be applied to exclusive domains. However, over time it is possible to see methods of computational social science applied to cross-domain problems.

6.3 Risks

Several risks are associated with a tactical Army agent-based capability. Getting ahead of the science is the foremost of the concerns; it is vital to avoid letting the engineering process of developing an agent-based capability outpace the science (Barry, Koehler, and Tivnan 2009). If engineering outpaces science, there can be the illusion of contextual oversimplification that results in users not trusting the capabilities that agent-based wargaming otherwise contributes. It is important to understand the difference between tool precision and robustness (Meyer 2012); both types of results provide very different conclusions.

Another risk is whether the validation of models and availability of the associated data is sufficient to ensure proper model validity (Hodges and Dewar 1992). The proposed Axtell–Epstein maturity framework identified and discussed in the prior section will help mitigate risk. However, the amount of time and effort the Army will need for this verification and validation process will be significant and should not be underestimated.

Finally, the study recommends the Army ruthlessly minimize the amount of time tactical users need to interact with and provide input to the produced tools and capabilities. In a tactical environment, time and simplicity are of the essence. If deemed appropriate, the Army could choose to allocate additional time to develop models stateside, and provide the models and/or results to the tactical user.

Other technical risks include effectively understanding and translating model results to action. Lessons learned from former ABM projects suggest that this risk may be addressed by providing guidance to users, so they can interpret what the model is communicating. Other risks include balancing idealized “thinness” or simplicity of agent rule sets with the broad abstractness of tactical situations the Army expects to model. Finally, historical culture within the Army tends to avoid planning the human aspect of conflict; plans to alter kinetic actions, due to consideration of Human Domain consequences, may be a difficult organizational proposition and change.

6.4 Comparable Technologies

Alternative procedural methods, such as game theory, include a variety of techniques to anticipate emergent consequences. Game Theory assumes a rational actor and makes assumptions that all players have some common knowledge. In the case of wargaming, motivation for winning the war is the argument for a rational actor. However, within different cultures and during asymmetric warfare, adversaries may not consider winning in the same way as the Army. Behavioral, Evolutionary and Low-rationality Game Theory are recent modifications to the original theory. In the first case, actor choices do not reflect benefits expected. In the second, beliefs and norms change over time. In the third, cognitive limitations affect the strategy space, and adaptive learning among strategies replaces the traditional utility maximization assumption. Reflexive Control is the former Soviet and current Russian evolution of game theory as applied to influencing the environment; in this case, the adversary will want to make the intended or constructed decision.

In addition to Game Theory, other methods may be useful. The technique of Points of Segmentation tries to identify a set of points that distinguishes individuals and groups with the goal of identifying possible points of cooperation and conflict. Prospect Theory describes the decision-making process of people, namely that people tend to be risk-taking with long-shot positive risk but risk averse when facing significant loss. Institutional Interactions is another systematic interaction model that allows participants to explore roles that influence capabilities and needs, similar to the current wargaming process. Morphological Analysis considers the entire space of possible implications; the analyst considers information abductively to derive judgments that could be useful (Ritchey 2011, 2014).

6.5 Technology Path

The study recommends the Army consider the following short-, medium- and long-term technology path to develop a tactical agent-based capability. For this study, the authors identify short term to be around 0–5 years in duration, medium term to be around 5–10 years, and long term to be 10 or more years. Table 5 and Fig. 33 identify individually identified research goals. The first illustration identifies broad-brush topics for each of the 4 recommendations. The study categorizes each research topic into the applicable recommendation and time horizon and provides brief summary descriptions in the following text. The second illustration uses a similar matrix of recommendation versus time horizon to identify specific technological capability recommendations. Similar to topics identified in the technology areas table, brief summarizations describe the capabilities.

Table 5 Table of recommended technology capabilities the Army should develop for a tactical agent-based capability in terms of time (i.e., near-, medium-, and long-term) and type

Recommendation	Near-term	Medium-term	Long-term
Army-centric agent-based modeling capability	Collect existing research and models Develop initial capabilities for each human domain sub-element that represents stylized facts Research architecture of cognitive models Identify reusable use-cases of integrating civil concerns into wargaming	Intuitive user-interface experimentation Improve quantitative macrolevel human domain model verification Applied research of cognitive reasoning agents Research inter-linkages/interactions between human domain elements GIS-integrated urban models	Microlevel models, stimulated by data (augmented computation) Influence of country and regional monitoring on tactical models Megacity urban models Dynamic culture models Low-rationality agents
Stateside repository	Data acquisition sufficient for quantitative macro models Collect and document best practices with existing tools Identify request for support workflows Develop version control workflow Using GIT technology	Library of models and research resources Ontology identifying modular component-level data communication Model verification and validation Workflow supported area of operations civil-population continuity	Data acquisition sufficient for modeling and verifying quantitative micro phenomena Integration application program interfaces (APIs) enabling access to operational data Model maintenance (re-validation) Running continuity models of areas of operations
Distributed application	Develop intuitive sliders user interface capability Research display capabilities for use in the field Distributed APIs for using AnyLogic modeling software	Monitoring and alerting of modeled conditions Web-based (in the browser) modelling Human on the loop (veto)	Monitoring and alerting when real-world COAs deviate from wargamed COAs Research model plug-and-play Human inside the loop (analyze) Integration of capability into DCGS–A
Training and proficiency	Develop warrant officer curriculum	Integration of curriculum into the schoolhouse	Certification of stateside library resources Certification of using ABM capabilities during wargaming

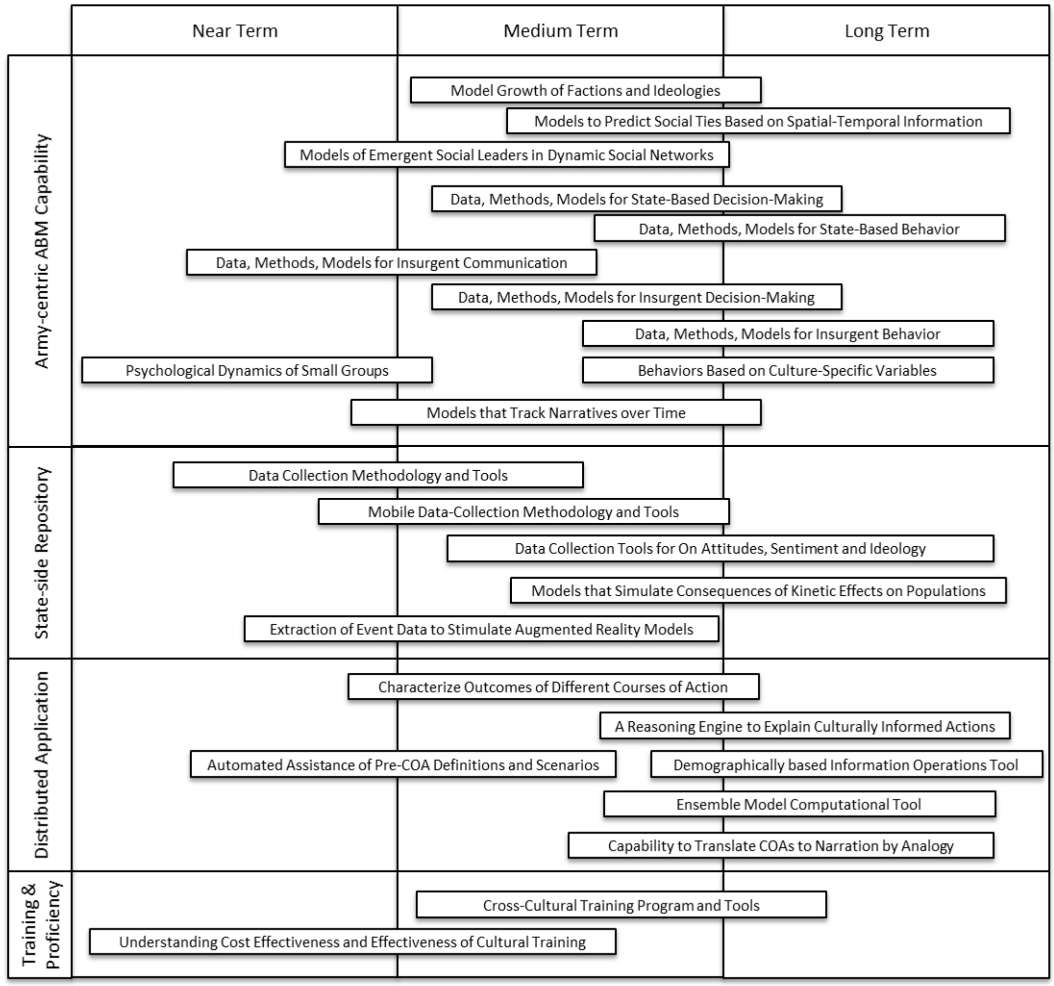

Fig. 33 Timeline of recommend capability developments identified in Table 5

6.5.1 Research Recommendations

Four research recommendations are proposed and grouped into the following areas: 1) Army-centric ABM capability, 2) forming a stateside repository, 3) implementing a distributed application and capability, and 4) providing applicable training and proficiency. Each of these 4 recommendations identifies technology areas containing individual research topics and categorized into near-, medium-, or long-term objectives. Following the table, brief summaries describe each research topic.

6.5.2 Army-Centric Agent-Based Modeling Capability: Near Term

Collect Existing Research and Models: The objective of this recommendation is to identify and document existing resources from both the academic and the government-sponsored communities and to make an index of these resources.

Develop Initial Capabilities for Each Human Domain Subelement that Represents Stylized Facts: There are 5 Human Domain elements, each of which has multiple subelements. However, a survey of current research (see Section 5) has indicated that only a small number of developed models simulate military-relevant conditions. The objective of this recommendation is to use existing research to create military-relevant models appropriate to each specific Human Domain sub element.

Research Architecture of Cognitive Models: Several cognitive approaches exist for agent-based architectures, such as belief–desire–intention and social-cognitive theories. The objective of this recommendation is to perform long-term research into the approaches and methodologies that can embody cognitive abilities into agents.

Identify Reusable Use-Cases of Integrating Civil Concerns into Wargaming: Tactical wargaming occurs across the breadth of military missions. The objective of this recommendation is to identify and build a library of notional or abstract representations of common tactical situations. Use-cases support subsequent recommendations, such as appropriate user interface development.

6.5.3 Army-Centric ABM Capability: Medium Term

Intuitive User-Interface Experimentation: A balance exists between model specificity, intuitiveness, and configurability. The objective of this recommendation is to identify an appropriate level of interaction, or "sliders," and correlated dependencies that a tactical-level analyst should be able to control to gain insight into possible situation consequences, without being overwhelmed in terms of data or amount of required time.

Improve Quantitative Macrolevel Human-Domain Model Verification: Models are characterized by their maturity level. According to the Axtell–Epstein Empirical Relevance Framework, the lowest level of model represents stylized facts or caricatures of macro phenomena. As maturity increases, models improve qualitative and quantitative representations of both macro- and microlevel phenomena. The objective of this recommendation is to improve individual Human Domain models, created in the near term, so they can more accurately represent macrolevel phenomena, ideally characterized with a degree of statistical relevance.

Applied Research of Cognitive Reasoning Agents: Agent-based models use probability distributions to represent agent decision-making processes. Cognitive reasoning has the potential to influence the nature of interactions between agents, with the goal of making models of these interactions more realistic or plausible. The objective of this recommendation is to incorporate research, performed in the near term, into cognitive processes to create additional versions of Human Domain models.

Research Interlinkages/Interactions between Human-Domain Elements: SOCOM has identified 5 Human Domain elements, each with multiple subelements. However, each subelement is not completely distinct from the others. The objective of this recommendation is to begin developing models that incorporate several independent Human Domain phenomena into distinct models. A challenge that comes with this recommendation is an increased burden on the collection, verification, and validation of the resulting model.

GIS-Integrated Urban Models: Modelers use different forms of nearness in agent-based models, such as grid-cell distance, Euclidean distance, and geospatial distance. For simplicity, many academic models use simple measures of distance, such as grid-cell distance or number of hops in a social network. The objective of this recommendation is to begin incorporating GIS representations of distance into existing models. In addition to incorporating simple GIS attributes, this research would also seek to integrate locations of urban components, such as roads and locations of buildings, into models.

6.5.4 Army-Centric ABM Capability: Long Term

Microlevel Models, Stimulated by Data (Augmented Computation): In the medium term, macrolevel maturity is the recommendation. However, as model maturity improves, so does the ability to characterize microlevel interactions and phenomena. Additional possibilities emerge as a result; one such possibility is for augmented simulation and computation. Augmented simulation models a synthetic version of the observed world and predicts future situations, which may emerge based on the current state. The objective of this recommendation is to improve the maturity of existing models so they can represent microlevel phenomena. A challenge accompanying this task is the collection and use of sufficient microlevel data.

Influence of Country and Regional Monitoring on Tactical Models: Initially, modelers build and test agent-based models without external influences or biases. At the tactical level, this keeps models simpler and easier to use. However, biases based on country and regional level models can provide insight into whether certain conditions may exist, such as a high probability of imminent conflict. The objective of this recommendation is to modify existing models to incorporate the context of biases into agents, interactions, and the environment.

Megacity Urban Models: The Army has identified the possibility of conflicts occurring within or around megacities, defined as cities with populations greater than 10 million. The objective of this recommendation is to create models that represent phenomena and resources representative of megacities (Ehlschlaeger et al. 2014). A challenge accompanying this task is the collection, verification, and validation of data, and identified phenomenology.

Dynamic Culture Models: ABM is a computational technique that can represent emergent phenomena. Other computational techniques, such as evolutionary game theory, are alternative computational means to embody changing states and situations over time. The objective of this recommendation is to create models that embody the phenomena of cultural evolution and the effect it has on agent interactions.

Low-Rationality Agents: Game theory is a computational technique that can identify the probability outcomes where the interest of multiple actors is involved. However, game theory assumes that all actors are rationally motivated. Research supporting prospect theory suggests rationality is not an appropriate decision-making assumption in all scenarios. The objective of this recommendation is to investigate how individual agents' decision-making distributions change depending on their specific situations and context.

6.5.5 Stateside Repository: Near Term

Data Acquisition Sufficient for Quantitative Macro Models: One challenge during the creation, verification, and validation of models is the use of appropriate data ensuring models is operating properly. Collection of data, specifically Human Domain data, is an essential task, on which other recommendations, such as model creation verified with proper macrolevel phenomena, depend. The objective of this recommendation is to identify and collect data that modelers are likely to use while creating and calibrating models. A difficulty within this task is to collect enough necessary and appropriate data, as required to model a diverse number of Human Domain elements and subelements.

Collect and Document Best Practices with Existing Tools: Similar to a recommendation within the Army-centric ABM track (see Section 6.5.2 and "Collect Existing Research and Models"), tools, and capabilities exist throughout the government and supporting contractor communities. Several of these tools were described in Section 5 (Existing Research and Applied Development of ABM), including IW TWG and SEAS/RWISE. The objective of this recommendation is to gather and store up-to-date versions of these capabilities for future use and reference. Additionally, this recommendation encompasses configuring tools to specific tactical Army needs, developing version control configurations and tools, and documenting best practices to interact with, configure, and test each capability.

In addition, this work should include documenting scenarios and use-cases the tool both can and cannot model appropriately.

Identify Request for Support Workflows: During the mid-2000s, JIEDDO set up COIC to support Request for Information (RFIs) from the warfighter. In many cases, requests for information directly supported tactical situations. A primary reason for recommending a stateside repository is to support tactical wargaming needs. The objective of this recommendation is to review the processes and workflows that COIC implemented in supporting its RFI system and to identify processes appropriate to support tactical wargaming requests.

Develop Version Control Workflow Using GIT Technology: The configurability of agent-based models may present yet another challenge. For example, if a stateside analyst is supporting a tactical analyst but the tactical analyst wants to make changes to the model, there needs to be a mechanism to enable, manage, and control differences and versions. GIT is a modern, distributed configuration and version management tool used in software development. The objective of this recommendation is to identify a workflow process, using a version control capability such as GIT, which allows multiple analysts to configure and track multiple versions of agent-based models. Thus, analysts could share and distribute models while ensuring they can be independently configured, depending on analysts' preferences.

6.5.6 Stateside Repository: Medium Term

Library of Models and Research Resources: This task is based on a prior recommendation (see Section 6.5.2, "Collect Existing Research, and Models") to collect existing research and models. The objective of this recommendation is to form a stateside repository that becomes a library of tactical wargaming models and research. The burden of identification, use, collection, and versioning of tactical wargaming models produced in the field may present a challenge to this recommendation.

Ontology Identifying Modular Component-Level Data Communication: Ontological representations are useful for inferring unstated information. Thus, ontologies could be useful for communicating mature model results, whereas incorporating ontologies into the executions of models may be less useful. The objective of this recommendation is to develop an ontology that serves as a plug-and-play connector, integrating disparate models together. A challenge with this task is that the ontology needs to be used as a standardized machine-to-machine communication language rather than to compute information.

Model Verification and Validation: Model maturity is essential if models are to become dependable. The objective of this recommendation is for the stateside repository to act as a quality control mechanism, with personnel supporting model validation. The breadth of the phenomena likely to be modeled may present a challenge, and it may also be difficult to ensure that the individuals doing the verification and validation are SMEs.

Workflow Supported Area of Operations Civil-Population Continuity: A difficulty with tactical-population interaction is the lack of continuity; deployed personnel change with regularity. A stateside support element could help provide and maintain continuity with local populations. The objective of this recommendation is ensure personnel and expectations for specific areas of operations are consistent and maintained over time, so each redeployment of tactical personnel are not starting over.

6.5.7 Stateside Repository: Long Term

Data Acquisition Sufficient for Modeling and Verifying Quantitative Micro Phenomena: In the long term, similar to the need for macrolevel data, microlevel data will be needed to model, verify, and validate microlevel phenomena. Moreover, the nature of the data collected will depend on the models created. The objective of this recommendation is for the stateside repository to collect and store microlevel data in anticipation of creating high-fidelity Human Domain models.

Integration APIs Enabling Access to Operational Data: As models become more capable and integrated within the wargaming process, there will likely be a need for timely operational data. Accessing operational data using automated tools presents a variety of integration challenges, and, as such, common APIs for accessing and parsing such data will likely be useful input to models. The objective of this recommendation is to create APIs that will translate operational data into appropriate model inputs. Both the breadth of translated data and the task of ensuring high quality automated translation will be challenges in implementing this recommendation.

Model Maintenance (Revalidation): Over time, models can become inaccurate because the assumptions used to create models change over time. Alternatively, the nature of the data collected may change over time. The objective of this recommendation is to ensure models, examples, documentation, and best practices are maintained and updated.

Running Continuity Models of Areas of Operations: In the long term, running continuous wargaming models that augment sensed reality is a unique military advantage. As tactical deployments cycle through areas of operations, units would have access to ongoing modeling resources and forecasts. The objective of this recommendation is for existing and mature wargaming resources to be available for use and configuration, with a minimal amount of up-front tactical time requirements.

6.5.8 Distributed Application: Near Term

Develop Intuitive "Sliders" User-Interface Capability: Several challenges exist for deploying agent-based models into a tactical environment. One of those challenges is ensuring models are relevant to tactical situations. Another is ensuring that interaction with given models is intuitive and useful for tactical users. The objective of this recommendation is to identify and develop user interfaces for the tactical user where a minimal number of "sliders" or variables may be altered but the model still provides valuable insights. In this case, "sliders" may not be limited to direct one-to-one alteration of model variables; for example, a single slide may alter the value of multiple variables proportionally.

Research Display Capabilities for Use in the Field: The unique demands of the tactical environment may not be best suited to the entire representation of agent-based models and their human–computer interfaces on a computer screen. Traditionally, tactical commanders use sand tables to communicate situations and plans to larger numbers of people. The objective of this recommendation is to investigate means of extending the user interface beyond the computer monitor. For example, one could calibrate the orientation of a display and project the scenario on the side of a tent to increase the viewing surface. Alternately, other research could investigate interacting with the model using touch or motion interfaces.

Distributed APIs for Using AnyLogic Modeling Software: In the short term, the study recommends use of the AnyLogic desktop-based, agent-based simulator. Other ABM frameworks exist, but AnyLogic is preferred because of its ease of use in the process of designing and testing agent-based models (Coles 2015; Grigoryev 2015). The objective of this recommendation is to create distributed processing APIs that models use while simulated by the AnyLogic tool. APIs enable the system to interact with other third-party systems and data that affect simulated results of the wargame.

6.5.9 Distributed Application: Medium Term

Monitoring and Alerting of Modeled Conditions: The goal of an agent-based model to provide nonexact but plausible simulations, based on identified scenarios. Automated tripwire or monitoring and alert capabilities can monitor wargaming states, similar to the way staff uses such capabilities in reality. The objective of this recommendation is to create APIs so monitoring and altering tools can be tested and configured using the wargaming scenario and simulation.

Web-Based (in the Browser) Modeling: In the long term, the goal is to run agent-based simulations in the browser so that installed programs are not needed. The objective of this recommendation is to develop or adapt ABM framework for use within the browser. Similar to desktop-based tools, web-based models need to exhibit ease of configurability, version control, and remote user interaction. Moreover, APIs enabling third-party data feeds need to be available.

Human on the Loop (Veto): While users are simulating agent-based models, they need to be able to control the simulation in a way analogous to a "god's-eye view" mode. For example, while the simulation is running, force specific agents to make decisions at specific times or locations. The objective of this recommendation is for the user to have control over decisions agents may make within the simulation, overriding normally used probability-based decision distributions. A challenge within this task is that it will be necessary to implement a "veto" mode, where the user does not take certain paths within the simulation without approval.

6.5.10 Distributed Application: Long Term

Monitoring and Alerting When Real-World COAs Deviate from Wargamed COAs: The objective of agent-based models, while simulating possible future interactions, is not to predict an exact future. Rather, the goal is to characterize possible situations that may exist in the future. A prior recommendation (see "Monitoring and Alerting of Modeled Conditions") suggested developing a synthetic simulation capability, paralleling the observable world. This recommendation expands on that concept, adding additional alteration capabilities. Specifically, the objective of this recommendation is to develop a monitoring and altering capability that notifies a user if real-world circumstances are deviating from the characterization of normally expected situations. One challenge to this task is the need to reduce false alarms by ensuring real-time observations and input data feeds are high quality.

Research Model Plug-and-Play: The current state-of-the-art procedure is to create models are that independent of each other. If a modeler combines 2 or more models, the resulting combination needs verification and validation as if it were a unique model. The objective of this recommendation is to investigate whether an ontology can mediate the combination of independent models in a dynamic fashion. It may be difficult to determine how to produce or prove automated verification and validation may occur.

Human inside the Loop (Analyze): In the long term, the authors envision the tactical user drawing from an existing library of models, simulating characteristics of the situation represented in reality. However, at some point, the stateside repository may have created and maintained pre-existing models for designated areas of operation. In that case, the tactical user would not need to model situations from scratch. The objective of this recommendation is to identify how the user may participate within the simulation, providing decision-making biases to agents within the simulation.

Integration of Capability into DCGS–A: DCGS–A is a program of record for Army intelligence systems. Over time, the goal of these intelligence capabilities is to be integrated and maintained within the DCGS–A environment. The objective of this recommendation is to ensure a successful transition of agent-based capabilities into DCGS–A, once the science and practicality of tactical model capabilities is demonstrated.

6.5.11 Training and Proficiency: Near Term

Develop Warrant Officer Curriculum: Wargaming is an essential component of the military decision-making process. However, tactical wargaming has been primarily taught as a manual process, nesting and synchronizing designated operations. Wargaming using agent-based modeling is a new capability to improve the rigor of tactical wargaming, specifically as Army operations relate to the civil population. The objective of this recommendation is to develop a training curriculum for the analysts who are most likely to use it at the tactical level. A challenge to this task is the limited amount of time available for training and the need to streamline communication of agent-based concepts necessary for the appropriate use of the capability.

6.5.12 Training and Proficiency: Medium Term

Integration of Curriculum into the Schoolhouse: Once a curriculum is developed, it needs formal Army approval and appropriate training tools. The objective of this recommendation is to integrate tactical wargame training into the warrant-officer schoolhouse and CGSC.

6.5.13 Training and Proficiency: Long Term

Certification of Stateside Library Resources: Once training is complete, a certification process ensures stakeholders are cognizant of the available resources. The objective of this recommendation is to create a certification that is renewed yearly or biyearly in warrant-officer training. Training and certification would be composed of a survey of available resources, their locations, and their abilities and limitations.

Certification of Using ABM Capabilities during Wargaming: Once initial training is complete, a follow-up process ensures training is both useful and applied in the field. The objective of this recommendation is to create a certification process ensuring personnel are aware of and trained regularly on changes to wargame modeling. This certification would provide examples of how other analysts used resources in realistic settings, based on lessons learned.

6.6 Capability Recommendations

As Office of Secretary Defense's HSCB Modeling Program neared completion, Boiney and Foster (2013) of MITRE, acting in its role of systems engineer, produced a summary document identifying social, cultural, and behavior modeling efforts (Schmorrow 2013). They categorized the multitude of funded projects into 4 capability areas: understand, detect, forecast, and mitigate. "Understand" refers to the capabilities that support perceptions and comprehension of socio-cultural features and dynamics. "Detect" identifies capabilities that discover, distinguish, and locate operationally relevant signatures. "Forecast" refers to capabilities for tracking and predicting change through sensing and modeling the environment. "Mitigate" involves courses of action with respect to information gleaned from the social and behavioral sciences.

Boiney and Foster summarize each of the 4 socio-cultural behavioral capabilities in terms of capability needs. They also identify recommended research aims for each category. This study identifies the following capabilities roadmap, which uses those recommendations as a starting point to identify capabilities relevant to the Human Domain and ABM.

6.6.1 Army-Centric ABM Capability

Psychological Dynamics of Small Groups: Research identifying small group decision-making dynamics exists within the academic community. However, the psychological aspect of small groups is not well modeled; as such, a capability addressing this psychological aspect needs to be developed. Challenges in developing this capability include collecting data to create and verify such a model and identifying or modeling the underlying psychological decision-making process of individual agents.

Data, Methods, Models for Insurgent Communication: The survey of existing Human Domain information (see Section 5, Existing Research and Applied Development of ABM) identified a deficiency in the means and methods of communicating information, regardless of the responsible party. Thus, an effective communication capability needs to be developed. Historically, these types of means and methods have been investigated for state actors to model military reaction times and procedures. Challenges in developing this capability include collecting data to verify such a model and keeping the model up-to-date with constantly emerging forms of communication.

Models of Emergent Social Leaders in Dynamic Social Networks: Models exist that represent interaction and projected results of political decision-makers; however, these models require copious amounts of time to investigate the relevant actors and identify their perspectives and resolutions to specific issues. This capability needs to be developed to reduce the amount of time needed to model emerging leaders within social networks that constantly change.

Models that Track Narratives over Time: Narrative text describes progressions of events through time. However, the underlying phenomena driving such interactions are often hidden to the external observer. Thus, models are needed that provide proper interpretations of text and the ability to form agents and interactions that support formation of the phenomena discussed in text.

Model Growth of Factions and Ideologies: As stated above, the decision-making processes of social groups have been investigated. However, existing research does not express the attribution of factions or the psychological dynamics of ideologies. Research is needed to address the decision-making results of populations to appropriately model growth of factions. To contribute to this research, sufficient data on decision-making results and population-level data regarding beliefs and ideologies need to be collected. Both these types of collected data are subject to inaccuracies for a variety of reasons, presenting a challenge to the development of accurate models.

Data, Methods, Models for State-Based Decision-Making: Many of the capability emphases addressed here concern nonstate actors. However, some recent events have demonstrated that state-based personnel can operate under different pretenses, suggesting a need to model state-actor-specific elements of decision-making (Thomas 2015). It may be difficult to model “informal” forms of command and control within the context of the civil population, or to collect observations regarding these types of interactions.

Data, Methods, Models for Insurgent Decision-Making: Analysis of decision-making is often reserved for the human analyst, so transferring this analysis to a more automated process presents challenges, such as the breadth of considerations that are incorporated into making decisions and the collection of the means and methods to verify proper model creation.

Models to Predict Social Ties Based on Spatial–Temporal Information: Research has indicated that movement to different locations over similar timespans can indicate the presence of social networks, which may then be modeled accordingly (Shen and Cheng 2016). A challenge in developing this capability is the collection of data that support model creation and verifying its accuracy.

Data, Methods, Models for Insurgent Behavior: According to some psychological theories, behavior is coupled to the agent's psychological state, suggesting that a model for psychological states may be developed. One challenge in developing this capability is developing a psychological agent model that accurately models reality. Another challenge is collecting enough data, with high enough resolution of insurgent behavior, to create and verify such models.

Behaviors Based on Culture-Specific Variables: Some psychological theories propose that culture is a component of the environment, with the result that its effects on behavior may be modeled. This capability must address the challenge of identifying whether individual behaviors are the result of environmental influences. If it is a result of culture, another challenge is identifying whether there is relationship between the strength of the culture and the behaviors exhibited.

Data, Methods, Models for State-Based Behavior: Estimation of state-based behaviors is often a hallmark of military versus military wargames. Developing a capability to estimate these behaviors needs to address the challenge of modeling the behavior of state-sponsored activities, which are under the pretense of operating outside formal state control.

6.6.2 Stateside Repository

Data-Collection Methodology and Tools: The objective of the stateside repository is to provide a reach-back capability to tactical wargamers. This is instantiated in several ways, one of which is to collect and publish data to create, verify, and validate models. A challenge in developing this capability is to identify and collect data that are appropriate for a wide variety of model development.

Extraction of Event Data to Stimulate Augmented-Reality Models: As model maturity grows, the expectation is that models will use APIs to external data sources to stimulate models. A challenge to this particular capability is to develop an extraction capability that can parse operational data and provide accurate inputs to wargaming model simulations.

Mobile Data-Collection Methodology and Tools: An essential aspect of model creation and verification is ensuring appropriate data are used to guide model interactions. Some of these needed data are expected to be collected in the field. A challenge in developing this capability is choosing the appropriate methodologies and means to collect the needed data.

Data Collection Tools for Attitudes, Sentiment, and Ideology: Sentiment analyses are derived from a variety of means including polls and salient textual attributes. However, a greater breadth and accuracy of collection information is expected to be necessary in the development of accurate Human Domain models.

Models that Simulate Consequences of Kinetic Effects on Populations: While a majority of the emphasis of recommended models is on Human Domain elements, kinetic effects also determine some aspects of population physiology. A challenge with modeling kinetic effects on the population capability is modeling long-term consequences on individual agents within the population, who as a whole population express resultant phenomenon.

6.6.3 Distributed Application

Automated Assistance of Pre-COA Definitions and Scenarios: Wargaming is the independent evaluation of several scenarios, each of which requires the identification of different situations. Thus, an automated capability is needed, which assists users in configuration each scenario before wargaming. This capability should be a support tool that effectively addresses the challenge of automatically creating and configuring large amounts of the wargame.

Characterize Outcomes of Different COAs: An agent-based model will produce a single output each time the simulation is run. However, that output is one of many possible outcomes, each of which could be the output of another simulation. This capability requires learning to characterize the expected output in the least amount of time possible.

Capability to Translate COAs to Narration by Analogy: When agent-based models are simulated, the output is generally a set of time-series charts. The user then needs to interpret and translate results into possible consequences. This capability is to translate the model output into user-understandable consequences. Once achieved, the capability should ideally translate that output into analogies with which the user is familiar, in order for the “lesson learned” to be communicated effectively.

A Reasoning Engine to Explain Culturally Informed Actions: Throughout the world, actions communicate different meanings. Culture and context help inform meaning. From a computational perspective, a reasoning engine could interpret the meaning of actions within different cultures. One challenge facing this capability is the need to address the breadth of cultures and situations required to translate the relevance of culturally biased actions.

Ensemble Model Computational Tool: Assuming all models are incorrect but some have value, this study suggests the developed wargaming tool run an ensemble of models to identify a wide range of possible emergent interactions. Since each model may use different assumptions, the capability will also need to ensure inputs and outputs, from each model is communicated appropriately.

Demographically Based Information Operations Tool: Once agent-based models are run and insights are identified, it would be useful to develop a tool that addresses how to use those insights effectively. One possibility is to alter inputs or adjust the models to account for demographic differences. The challenge is to develop an automated means of making model changes, emulating specific demographic attributes, to simulate proposed information operations. This capability would likely require a large enough data collection to test proposed information operations' messages with confidence.

6.6.4 Training and Proficiency

Understanding Cost Effectiveness and Effectiveness of Cultural Training: A baseline of training efficacy is needed to understand whether improvements need to be made or have been successfully implemented. This capability should identify the goals and objectives of training and identify the proper metrics to measure an improvement in effectiveness.

Cross-Cultural Training Program and Tools: Once demographic and culture-specific goals and objectives are identified, training tools and resources need to be identified and developed. It is essential to communicate the value of cultural differences to trainees so they understand the nuances of what they are trying to accomplish.

6.7 Training and Resource Implications

Similar to other specialized capabilities and technologies, tactical agent-based wargaming requires a proper understanding and skill set to produce expected results. Four criteria are essential for an effective training program: curriculum, theory, practice, and ongoing proficiency. "Curriculum" identifies what the authors believe are essential elements to an appropriate training curriculum. This study identifies curriculum resources available from both government and academic sources. "Theory" identifies topics of interest and their relevance to ABM. "Practice" identifies several of the practical concerns one would need to be aware of when operating with a degree of proficiency. Finally, “proficiency” identifies evaluating ongoing knowledge in tactical ABM capabilities.

6.7.1 Curriculum

A wargaming curriculum is composed of several resources and perspectives. Firstly, a survey and recounting of wargaming history is essential to newly trained personnel. Summarization provides both context and practical rationale for wargaming. Despite the amount of effort wargaming requires, it has real value and provides stakeholders with advantages once participants have worked through scenarios. Ideally, both forms of wargaming—traditional and *Free Kriegsspiel*—are taught to trainees in the context of historical use-cases, results, and lessons learned (Caffrey 2000).

Secondly, while the Army is a separate organization than the Special Forces, ARSOF training perspectives may offer insight into components of wargaming curricula. Special Forces personnel are trained and are qualified in both military skills and specific regional languages and cultures of the world. This study suggests the Army adopt a similar perspective for a wargaming specialization. Some wargaming students should specialize in traditional force-on-force wargaming, while others should specialize in Human Domain topics specific to different areas of the world. A holistic training perspective is likely to allow Army personnel to become more proficient and effective. Moreover, a holistic form of training supports the modern Army “Design” concept.

Thirdly, several existing Army-centric wargaming resources are available to students, namely the following 2 books:

- *Student Text 100-9, Techniques and Procedures for Tactical Decision-Making* (1991)
- *Student Text, Version 2, Art of Design* (2010)

In an academic setting, several institutions offer courses in Computational Social Science. George Mason University is one such institution offering courses that teach ABM. Resources for such a course are also independently available; Dr Axtell (2013) recommends the following texts for CSS 610–Computational Analysis of Social Complexity:

- Epstein JM, Axtell R. *Growing Artificial Societies: Social Science from the Bottom Up* (1996)
- Leemis L, Park S. *Discrete-Event Simulation: A First Course* (2004)

- Railsback SF, Grimm V. *Agent-Based and Individual-Based Modeling: A Practical Introduction* (2011)
- Schelling TC. *Micromotives and Macrobehavior* (1978)
- Heppenstall AJ, Crooks AT, See LM, Batty M. *Agent-Based Models of Geographical Systems* (2012)
- Shoham Y, Layton-Brown K. *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations* (2008)
- Weiss G. *Multiagent Systems: A Modern Approach to Distributed Artificial Intelligence* (1999)

Fourthly, several institutions, including the Army Culture Center and the Naval Postgraduate School, would likely provide valuable resources. The Army's TRADOC Culture Center was established during the mid-2000s to improve Soldier's cultural awareness to situations they would likely encounter (Bird 2007; Connable 2009). The Naval Postgraduate School offers wargaming training in other domains but it is likely that some crossover exists between curriculums (Naval Postgraduate School 2015).

6.7.2 Theory

The theory component comprises several topics relevant to ABM, ranging from social sciences to math, and seeks to integrate computational techniques with cultural intricacies. This study identifies 6 topics, each of which could be an individual course. These include in order of priority, the following: 1) Culture and Modern-Day Tribes, 2) Complex Adaptive Systems, 3) Applied Complex Systems, 4) Survey of Game Theory, 5) Applied Microsoft Excel Analysis, and 6) Applied Statistics.

A study of culture and modern-day tribes would identify the need to understand culture down to a tribal level. In the Middle East, a clear designation of a tribe may exist. However, in Western culture, a tribe may be more analogous to a company and the culture that it embodies. Culture both shapes the environment within which people operate and influences their perception of the world. Recent conflicts in both Iraq and Afghanistan have demonstrated a need to understand the underlying culture of an area of operations and conflict.

The study of complex adaptive systems would explore a field of study known as complexity science. Complex refers to dynamic interactions, where relationships are not aggregations of individual entities. Adaptive refers to change by individual entities and, because of interactions, collective behavior changes. Complex adaptive systems are similar to multiagent systems, but complex adaptive systems focus on macro behavior whereas multiagent systems focus on individual behavior.

Applied complex systems are a second iteration on the aforementioned complex adaptive systems topic. However, this second iteration would emphasize the application and exploration of such systems. For example, it would incorporate the study of the rules within agents that cause emergent phenomena at the macrolevel.

A survey course of game theory and its derivatives would review related mathematical expressions of game theory. Agent-based modeling and game theory are slightly different because game theory assumes rational actors and homogenous agent information and ABM does not. However, game theory is still useful in gaining understanding of dynamics and interaction between agents. Its derivatives include behavioral game theory, evolutionary game theory, low-rationality game theory, prospect theory, and reflexive control.

Applied Microsoft Excel analysis would be a practical training course and would ensure trainees have some familiarity with data analysis and are proficient with Excel, so they can use spreadsheets to input data into simulations and use Excel to analyze results.

Applied statistics is the last recommended training topic. Statistics are essential to ABM because, for example, statistics represent decision-making distributions used by agents. It is also useful in characterizing the nature of the output produced from agent-based simulations.

6.7.3 Practice

The practice component identifies practical concerns one would need to know to use agent-based capabilities and tools. Available ABM tools would ideally use a form of version control technology, which allows users to snapshot individual iterations of models and their configurations. For example, version control technology allows individuals to share models and configurations, allows a third party to make changes, and allows the ability to receive and approve all, some, or none of the changes. Modeling tools may operate in a connected or disconnected mode. In a connected mode, properly built models can use large clusters of computers to assist in computations. In a disconnected mode, the user only has their local computer to perform computations. As a result, the user may be limited in the number of simulations that can characterize model results.

“Practice” also includes techniques used to develop and edit agent-based models. Similar to a mechanic working with an engine, the user should ideally have a working knowledge of how models operate. Trainees should be aware of existing agent-based models and supporting capabilities. Finally, the trainees need to know how to use and interpret results displayed on the modeling tool's user interface, such as maps, charts, and time-series representations. Trainees should also know how to analyze model data exported to Excel.

6.7.4 Proficiency

The proficiency component includes a combination of stateside support and regular certifications that evaluate whether the user is familiar and proficient with available modeling tools and existing agent-based models. Stateside support is a reach-back support mechanism available to tactical wargamers. If working properly, stateside support should collaboratively support the tactical user's needs. Certifications ensure that the user is familiar with changes in published models and capabilities available from the stateside repository.

6.8 Summary

In this section, the report identified and discussed 4 recommendations for using an ABM capability to improve the rigor of tactical wargaming. Challenges to agent-based wargaming capacity include a wide breadth of research topics. The study identifies surveyed and comparable technologies, such as game theory and its derivatives, and detailed the agent-based potential, limitations, and risks. Finally, the study discusses a recommended technology and research path for the Army. The study concludes that ABM would increase the rigor of tactical wargaming, especially if the Army would like to consider the consequences and interactions of its actions with local populations.

7. Conclusion

Future warfare will likely remain characterized by uncertainty and commanders, their planning staffs, and intelligence analysts will encounter a range of known, knowable, complex, and chaotic problems. ABM and its resulting emergent behavior is a potential solution to model terrain in terms of the Human Domain and improve the results and rigor of the traditional wargaming process.

Some risk is associated with developing a tactical Army agent-based capability. Researching and developing an Army-centric ABM capability is a nontrivial task. One of the concerns is allowing engineering to get ahead of the modeled science. If engineering outpaces science, there can be the illusion of contextual oversimplification that results in users not trusting the capabilities that agent-based wargaming otherwise contributes.

The Army will need to devote significant person-hours to perform leading research and development, adequate verification and validation, subsequent model creation, and resource revisions. Similarly, a nontrivial amount of money, appropriated throughout the range of Basic Research–Operational System Development money, and people, serving in both stateside and training positions, will be required.

Finally, the authors recommend the Army consider using a tactical agent-based capability during wargaming, down to the brigade. If the Army decides it does not want to use an agent-based capability, this report recommends at least being prepared for an adversary to use it.

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Appendix A. Survey of Existing Agent-Based Modeling Frameworks

This appendix appears in its original form, without editorial change.

The following is a sampling of existing agent-based modeling frameworks. For the purpose of this Appendix, the study separates the identified frameworks into three groups based on an initial assessment of their maturity: most mature, intermediate maturity, and low maturity or unmaintained. Most mature indicates the likelihood of continual use and a well-developed capability. Intermediate maturity indicates still relevant research and capabilities but the concepts may not be fully realized. Low maturity, or appears to be unmaintained, identifies available frameworks but, at this time, the study does not recommend their use.

Each of the following seventy-two frameworks is identified by its name, its estimated use (e.g., Academic-Advanced), estimated last update, location, and a brief description. Estimated use is identified as one of the following enumerations: Academic-Advanced, Academic-Intermediate, Academic-Basic, Commercial, and Government. Descriptions use text from the respective projects' web site.

A.1 Most Mature Frameworks

ACT-R	**Academic-Advanced**	**Updated: 2016**

http://act-r.psy.cmu.edu/
ACT-R is a cognitive architecture: a theory for simulating and understanding human cognition. Researchers working on ACT-R strive to understand how people organize knowledge and produce intelligent behavior.

AgentBase	**Academic-Advanced**	**Updated: 2016**

http://agentbase.org/
AgentBase.org allows you to do Agent-Based Modeling (ABM) in the browser. You can edit, save, and share models without installing any software or even reloading the page. Models are written in Coffeescript, and use the AgentBase library.

AgentScript	**Academic-Advanced**	**Updated: 2016**

http://agentscript.org/
AgentScript is a minimalist Agent-Based Modeling (ABM) framework based on NetLogo agent semantics. Its goal is to promote the Agent Oriented Programming model in a highly deployable CoffeeScript/JavaScript implementation.

AMP (Agent Modeling Platform)	**Academic-Advanced**	**Updated: 2015**

http://eclipse.org/amp/
The AMP project provides extensible frameworks and exemplary tools for representing, editing, generating, executing, and visualizing agent-based models (ABMs) and any other domain requiring spatial, behavioral, and functional features.

AnyLogic	**Commercial**	**Updated: 2016**

http://www.anylogic.com
AnyLogic is the only simulation tool that supports all the most common simulation methodologies in place today: System Dynamics, Process-centric (AKA Discrete Event), and Agent-Based modeling. The object-oriented model design paradigm supported by AnyLogic provides for modular, hierarchical, and incremental construction of large models.

Ascape	Academic-Advanced	Updated: 2013

http://ascape.sourceforge.net/
Models can be developed in Ascape using far less code than in other tools. Ascape models are easier to explore, and profound changes to the models can be made with minimal code changes. Ascape offers a broad array of modeling and visualization tools.

Behavior Composer	Academic-Advanced	Updated: 2015

http://m.modelling4all.org
The Modelling4All Project is building a web-based tool for constructing, running, visualizing, analyzing, and sharing agent-based models. These models can be constructed by non-experts by composing pre-built modular components called micro-behaviors.

Brahms	Academic-Advanced	Updated: 2012

http://brahms.sourceforge.net/docs/
BRAHMS is a Modular Execution Framework (MEF) for executing integrated systems built from component software processes (a SystemML-ready execution client). Its operation is conceptually similar to that of Simulink, for example.

Cougaar	Government	Updated: 2015

http://cougaar.org
Cougaar is a Java-based architecture for the construction of large-scale distributed agent-based applications. It is a product of two consecutive, multi-year DARPA research programs (UltraLog) into large-scale agent systems spanning eight years of effort.

CybelePro	Commercial	Updated: 2014

http://www.i-a-i.com/?core/modeling-and-simulation/distributed-architectures-and-solutions
CybelePro is the underlying agent framework of NASA’s Airspace Concept Evaluation System, a distributed gate-to-gate simulator of the ATM operations in the National Airspace. For applications in network modeling and simulation our Agent-Based Parallel Discrete Event Simulation Framework, enables the execution of large-scale (10,000s of communicating nodes), high fidelity, mobile, tactical (primarily wireless) network models in a parallel computing environment, where each computing node is a multi-core processor.

GAMA	Academic-Advanced	Updated: 2016

https://github.com/gama-platform
GAMA is a modeling and simulation development environment for building spatially explicit agent-based simulations.

Gambit	Academic-Advanced	Updated: 2016

http://www.gambit-project.org/
Gambit is an open-source collection of tools for doing computation in game theory. With Gambit, you can build, analyze, and explore game theoretical models.

GoldSim	Commercial	Updated: 2016

http://www.goldsim.com/Home/
GoldSim is a general-purpose simulator that utilizes a hybrid of several simulation approaches, combining an extension of system dynamics with some aspects of discrete event simulation, and embedding the dynamic simulation engine within a Monte Carlo simulation framework.

iGen	Commercial	Updated: 2010

http://www.chisystems.com/cognitivemodel.html
iGEN is a patented artificial intelligence engine that mimics the way human experts analyze and make decisions in a wide range of situations. iGEN uses a revolutionary psychological model of human thought and problem solving called COGNET within an engineering-oriented integrated software development environment.

Insight Maker	**Commercial**	**Updated: 2016**
https://insightmaker.com/ Insight Maker runs in your web-browser. No downloads or plugins are needed. Explore powerful simulation algorithms for System Dynamics and Agent-Based Modeling in a truly cohesive environment.		

JABM	**Academic-Advanced**	**Updated: 2016**
http://jabm.sourceforge.net/ The Java Agent-Based Modelling (JABM) toolkit is a Java framework for building agent-based models using a discrete-event simulation framework.		

JADE	**Commercial**	**Updated: 2015**
http://jade.tilab.com/ JADE (Java Agent DEvelopment Framework) is a software Framework fully implemented in the Java language. Besides the agent abstraction, JADE provides a simple yet powerful task execution and composition model, peer to peer agent communication based on the asynchronous message passing paradigm, a yellow pages service supporting publish subscribe discovery mechanism and many other advanced features that facilitates the development of a distributed system.		

MaDKit (Multi Agent Development Kit)	**Academic-Advanced**	**Updated: 2016**
http://www.madkit.org/ MaDKit is a lightweight Java library for designing and simulating Multi-Agent Systems (MAS). In contrast to conventional approaches, which are mostly agent-centered, MaDKit follows an organization-centered approach (OCMAS) so that there is no predefined agent model in MaDKit. So, MaDKit is built upon the AGR (Agent/Group/Role) organizational model: agents play roles in groups and thus create artificial societies.		

MASON	**Academic-Advanced**	**Updated: 2015**
https://cs.gmu.edu/~eclab/projects/mason/ MASON is a fast discrete-event multi-agent simulation library core in Java, designed to be the foundation for large custom-purpose Java simulations, and to provide more than enough functionality for many lightweight simulation needs.		

NetLogo	**Academic-Advanced**	**Updated: 2016**
https://ccl.northwestern.edu/netlogo/index.shtml NetLogo is a multi-agent programmable modeling environment. Tens of thousands of students, teachers, and researchers use it worldwide. It also powers HubNet participatory simulations.		

PS-I (Political Science-Identity)	**Government**	**Updated: 2014**
http://ps-i.sourceforge.net/ Ps-i is an environment for running agent-based simulations. It is cross-platform, with binaries available for Win32.		

Repast	**Academic-Advanced**	**Updated: 2015**
http://repast.sourceforge.net/ The Repast Suite is a family of advanced, free, and open source agent-based modeling and simulation platforms that have collectively been under continuous development for over 15 years.		

SEAS (System Effectiveness Analysis Simulation)	Government	Updated: 2015

https://www.teamseas.com/
The System Effectiveness Analysis Simulation (SEAS) is a constructive modeling and simulation tool that enables mission-level Military Utility Analysis (MUA). SEAS offers a powerful agent-based modeling environment that allows the analyst to simulate the complex, adaptive interactions of opposing military forces in a physics-based battlespace. Agents (units and platforms) execute programmable behavioral and decision-making rules based on battlespace perception. The interaction of the agents with each other and their environment results in warfighting outcomes, enabling Military Utility Analysis.

SimPy	Academic-Advanced	Updated: 2016

https://simpy.readthedocs.org/en/latest/
SimPy is a process-based discrete-event simulation framework based on standard Python. Its event dispatcher is based on Python's generators and can also be used for asynchronous networking or to implement multi-agent systems (with both, simulated and real communication).

SimX	Commercial	Updated: 2014

https://github.com/sim-x/simx
SimX is a library for developing parallel, discrete-event simulations in Python. SimX also supports process-oriented simulations. Parallel simulations are implemented using distributed memory and message passing.

SOAR	Academic-Advanced	Updated: 2016

http://soar.eecs.umich.edu/
Soar is a general cognitive architecture for developing systems that exhibit intelligent behavior. Researchers all over the world, both from the fields of artificial intelligence and cognitive science, are using Soar for a variety of tasks. It has been in use since 1983, evolving through many different versions to where it is now Soar, Version 9.

Sugarscape	Academic-Advanced	Updated: 2013

http://sugarscape.sourceforge.net/
Sugarscape is an 'artificially intelligent agent-based social simulation'. Epstein & Axtell's implementation came to be known as the Sugarscape model and it is from that work that this project derives its name.

Swarm	Academic-Advanced	Updated: 2013

http://www.swarm.org/wiki/Swarm_main_page
Swarm is a platform for agent-based models (ABMs) that include a conceptual framework for designing, describing, and conducting experiments on ABMs; software implementing that framework and providing many handy tools; and a community of users and developers that share ideas, software, and experience.

Vensim	Commercial	Updated: 2015

http://vensim.com/vensim
Vensim is simulation software for improving the performance of real systems. Vensim is used for developing, analyzing, and packaging dynamic feedback models.

A.2 Intermediate Maturity Frameworks

AgentService	**Academic-advanced**	**Updated: 2009**
http://www.AgentService.it AgentService is an agent oriented programming framework based on the Common Language Infrastructure (CLI) and the C# language. The key features of AgentService are the new agent model that exploits the innovative scheduling features of the CLI and the software platform providing the agents with advanced run-time services.		

AgentSheets	**Commercial**	**Updated: 2015**
http://www.agentsheets.com/products/index.html AgentSheets is a revolutionary tool that lets you create your own agent-based games and simulations and publish them on the Web through a user-friendly drag-and-drop interface.		

AOR simulation	**Academic-intermediate**	**Updated: 2010**
http://oxygen.informatik.tu-cottbus.de/aor/?q=node/2 The Entity-Relationship (ER) and Agent-Object-Relationship (AOR) modeling and simulation framework developed at the Brandenburg University of Technology, Germany, provides the XML-based simulation languages ERSL and its superset AORSL for basic and agent-based discrete event simulation.		

BDI4Jade	**Academic-advanced**	**Updated: 2014**
http://www.inf.ufrgs.br/prosoft/bdi4jade/ BDI4JADE is an agent platform that implements the BDI (belief-desire-intention) architecture. It consists of a BDI layer implemented on top of JADE.		

Cormas (common-pool resources and multi-agent systems)	**Academic-intermediate**	**Updated: 2012**
http://cormas.cirad.fr/indexeng.htm Cormas is intended to facilitate the design of ABM as well as the monitoring and analysis of simulation scenarios. It is used by an international community of researchers willing to understand the relationships between societies and their environment.		

DALI	**Academic-intermediate**	**Updated: 2016**
https://github.com/AAAI-DISIM-UnivAQ/DALI A Multi Agent Systems Framework built on top of Sicstus Prolog.		

ENVISION	**Academic-advanced**	**Updated: 2015**
http://envision.bioe.orst.edu/ ENVISION is a GIS-based tool for scenario-based community and regional integrated planning and environmental assessments. It provides a robust platform for integrating a variety of spatially explicit models of landscape change processes and production for conducting alternative futures analyses.		

FLAME	**Academic-advanced**	**Updated: 2014**
http://www.flame.ac.uk/ FLAME is a generic agent-based modelling system, which can be used to development applications in many areas. The FLAME framework is an enabling tool to create agent-based models that can be run on high performance computers (HPCs).		

GROWlab	Academic-advanced	Updated: 2008

http://www.icr.ethz.ch/research/growlab
Computer simulation has proved to be a vital adjunct to traditional approaches of understanding social phenomena in fully understanding the dynamics of individual and collective actions.

JAMEL (java agent-based macroeconomic laboratory)	Academic-intermediate	Updated: 2016

http://p.seppecher.free.fr/jamel/
Jamel (Java Agent-based Macro-Economic Laboratory) is an open source agent-based framework dedicated to the modeling, the simulation, and the analysis of complex monetary economies.

JAMSIM	Academic-basic	Updated: 2012

https://ideas.repec.org/a/jas/jasssj/2011-26-2.html
JAMSIM (JAva MicroSIMulation) is an innovative synthesis of open source packages that provides an environment and set of features for the creation of dynamic discrete-time microsimulation models that are to be executed, manipulated, and interrogated by non-technical, policy-oriented users. Combining the leading open source statistical package R and one of the foremost agent-based modelling (ABM) graphical tools Ascape, JAMSIM is available as an open source tool, for public reuse and modification.

JANUS	Academic-advanced	Updated: 2016

http://www.janusproject.io/
Janus is an open-source multi-agent platform fully implemented in Java 1.7. Janus enables developers to quickly create web, enterprise, and desktop multi-agent-based applications.

JAS	Academic-intermediate	Updated: 2006

http://jaslibrary.sourceforge.net/index.html
JAS is a Java toolkit for creating agent-based simulations.
It features a discrete-event time engine, statistical probes with Hypersonic database built-in storage capability, Neural Networks and Genetic Algorithms packages, and graph support for Social Network Analysis.

JASA (Java auction simulator API)	Academic-intermediate	Updated: 2014

http://jasa.sourceforge.net/
JASA is a high-performance auction simulator. It is designed for performing experiments in agent-based computational economics.

JIAC	Academic-advanced	Updated: 2016

http://www.jiac.de/
JIAC (Java-based Intelligent Agent Componentware) is a Java-based agent architecture and framework that eases the development and the operation of large-scale, distributed applications and services. The framework supports the design, implementation, and deployment of software agent systems.

LSD (laboratory for simulation development)	Academic-intermediate	Updated: 2015

http://www.labsimdev.org/Joomla_1-3/
LSD implements discrete-time simulations, expressing the results as series of values for each variable in the model. Being based on C++, LSD models are extremely fast and efficient, allowing for even huge models. LSD is particularly suited to implement agent-based models.

MADeM (multi-model agent decision making)	**Academic-intermediate**	**Updated: 2015**

http://www.uv.es/grimo/jmadem/
The MADeM (Multi-modal Agent Decision Making) model provides agents with a general mechanism to make socially acceptable decisions. In this kind of decisions, the members of an organization are required to express their preferences with regard to the different solutions for a specific decision problem.

MASS (multi-agent simulation suite)	**Commercial**	**Updated: 2012**

http://www.aitia.ai/en/web/iaws/mass
The Multi Agent Simulation Suite consists of four applications offering solutions for different aspects of modeling. Each of the applications is developed with the intention of providing professional tools for users without heavy programming skills. The components include functional agent-based language for simulations, visualization module, model exploration module, and participatory extension.

MATSim	**Academic-advanced**	**Updated: 2016**

http://www.matsim.org/
MATSim is an open-source framework to implement large-scale agent-based transport simulations. Currently, MATSim offers a framework for demand-modeling, agent-based mobility-simulation (traffic flow simulation), re-planning, and a controller to run simulations as well as methods to analyze the output generated by the modules.

Mesa	**Academic-intermediate**	**Updated: 2016**

https://pypi.python.org/pypi/Mesa/
Mesa is an Apache2 licensed agent-based modeling (or ABM) framework in Python. It allows users to quickly create agent-based models using built-in core components (such as spatial grids and agent schedulers) or customized implementations; visualize them using a browser-based interface; and analyze their results using Python's data analysis tools. Its goal is to be the Python 3-based alternative to NetLogo, Repast, or MASON.

Modgen	**Government**	**Updated: 2015**

http://www.statcan.gc.ca/microsimulation/modgen/modgen-eng.htm
Modgen (Model generator) is a generic microsimulation programming language supporting the creation, maintenance, and documentation of dynamic microsimulation models. Several types of models can be accommodated, be they continuous or discrete time, with interacting or non-interacting populations.

Pandora	**Academic-intermediate**	**Updated: 2016**

http://www.bsc.es/computer-applications/pandora-hpc-agent-based-modelling-framework
Pandora Library is an ABM framework created by the social simulation research group of the Barcelona Supercomputing Centre. This tool is designed to implement agent-based models and to execute them in high-performance computing environments.

StarLogo Nova	**Academic-advanced**	**Updated: 2014**

http://www.slnova.org/
StarLogo Nova is the new online iteration of StarLogo, following in StarLogo TNG's footsteps. StarLogo Nova builds upon TNG's innovations, with several language refinements and new features.

TNG	Academic-Advanced	Updated: 2016
http://www2.econ.iastate.edu/tesfatsi/tnghome.htm Trade Network Game (TNG) is a framework for studying the formation and evolution of trade networks among strategically interacting traders (Buyers, Sellers, and Dealers) operating under variously specified market protocols.		

Xholon	Commercial	Updated: 2014
http://www.primordion.com/Xholon/ Xholon is a flexible open source tool for multi-paradigm modeling, simulation, design, execution, and transformation. Generic Java and XML building blocks are extended into multiple domains, and woven into loosely organized systems.		

A.3 Low Maturity Frameworks (or Possibly Unmaintained)

ABLE (agent building and learning environment)	Commercial	Updated: 2005
http://www.freecode.com/projects/agentbuildingandlearningenvironmentforlinux Agent Building and Learning Enviroment (ABLE) is a Java framework, component library, and productivity tool kit for building intelligent agents using machine learning and reasoning. With this tool, developers can implement their own AbleBeans and AbleAgents and plug them into ABLE's Agent Editor.		

AgentBuilder	Commercial	Updated: 2011
http://www.agentbuilder.com AgentBuilder is an integrated software toolkit that allows software developers to quickly develop intelligent software agents and agent-based applications.		

Breve	Academic-intermediate	Updated: 2008
http://www.spiderland.org breve is a free, open-source software package which makes it easy to build 3D simulations of multi-agent systems and artificial life. Using Python, or using a simple scripting language called steve, you can define the behaviors of agents in a 3D world and observe how they interact. breve includes physical simulation and collision detection so you can simulate realistic creatures, and an OpenGL display engine so you can visualize your simulated worlds.		

DigiHive	Academic-intermediate	Updated: 2011
http://www.swarm.eti.pg.gda.pl/index.htm The DigiHive environment is an original, artificial, complete, low level, and closed environment consisting of space, moving objects, and rules, which govern their interactions.		

D-OMAR (distributed operator model architecture)	Government	Updated: 1999
http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA364623 Distributed OMAR (D-OMAR) is a new implementation of the Operator Model Architecture (OMAR) designed to operate in a distributed computing environment. As in OMAR, D-OMAR is designed as a simulation environment in which to create human performance models. It also provides the capability to develop the complex multi-tasking agents that are needed in agent-based systems.		

JCA-Sim	Academic-intermediate	Updated: 2004

http://www.jcasim.de/#Overview
The program system JCASim is a general-purpose system for simulating cellular automata in Java. It includes a stand-alone application and an applet for web presentations.

jES (Java enterprise simulator)	Academic-intermediate	Updated: 2015

http://terna.to.it/jes/
jES, the synthetic name of the Java Enterprise Simulator project, is a frame used to develop enterprise simulation models based on the Java version of Swarm both (1) to simulate the activities ‑ and the consistent emerging results ‑ of an actual enterprise, and (2) to build virtual or hypothetical enterprises.

MAML (multi-agent modeling language)	Academic-advanced	Updated: 1999

http://www.maml.hu/maml/initiative/index.html
The current version of MAML is an extension to Objective-C (using the Swarm libraries). It consists of a couple of 'macro-keywords' that define the general structure of a simulation. The remaining is filled with pure swarm-code. A MAML-to-Swarm (named xmc) compiler is being developed, which compiles the source code into a swarm application. Like every other Swarm application, this generated application must be compiled by gcc.

MAS-SOC (multi-agent simulations for the SOCial sciences)	Academic-advanced	Updated: 2005

http://jasss.soc.surrey.ac.uk/8/3/7.html
One of the main goals of the MAS-SOC simulation platform (MAS-SOC stands for Multi-Agent Simulations for the SOCial Sciences) is to provide a framework for the creation of agent-based simulations, which does not require too much experience in programming from users, yet allowing users to use state-of-the-art agent technologies. In particular, it should allow for the design and implementation of simulations with cognitive agents -- a plethora of platforms for reactive agents exists, but that is certainly not the case for agents that are more elaborate.

Mimosa	Government	Updated: 2014

http://mimosa.sourceforge.net
Mimosa is a modeling and simulation platform, covering the process from building conceptual models to running the simulations. The specification use ontologies and an extensible set of formalisms for the dynamics, initialization, and visualization. The simulation kernel is based on DEVS.

MIMOSE (micro-und multilevel modelling software)	Academic-basic	Updated: 1999

http://userpages.uni-koblenz.de/~moeh/projekte/mimose.html
The main purpose of the MIMOSE project was the development of a modelling language, which considers special demands of modelling in social science, especially the description of nonlinear, quantitative, and qualitative relations, stochastic influences, birth, and death processes, as well as micro and multilevel models.

MobiDyc	Academic-intermediate	Updated: 2006

http://w3.avignon.inra.fr/mobidyc/index.php/English_summary
Mobidyc is a software project that aims to promote Individual-Based Modelling in the field of ecology, biology, and environment. It is the acronym for MOdelling Based on Individuals for the DYnamics of Communities.

Moduleco	**Academic-basic**	**Updated: 2001**

http://www.gemass.fr/dphan/moduleco/english/moduleco00.htm
Moduleco is a multi-agent modular framework for the simulation of network effects and population dynamics in social sciences, markets, and organizations.

MOOSE (multimodeling object-oriented simulation environment)	**Academic-intermediate**	**Updated: 1997**

http://www.cise.ufl.edu/~fishwick/moose.html
MOOSE is the next generation of SimPack which was initiated in 1990 for providing a general-purpose toolkit of C and C++ libraries for discrete-event and continuous simulation.

SimAgent	**Academic-intermediate**	**Updated: 2014**

http://www.cs.bham.ac.uk/research/projects/poplog/packages/simagent.html
Like ACT-R, COGENT, and the original SOAR, SimAgent is primarily designed to support design and implementation of very complex agents, each composed of very different interacting components (like a human mind) where the whole thing is embedded in an environment that could be a mixture of physical objects and other agents of many sorts.

TerraME	**Academic-advanced**	**Updated: 2013**

http://www.terrame.org/doku.php
TerraME is a programming environment for spatial dynamical modelling. It supports cellular automata, agent-based models, and network models running in 2D cell spaces. TerraME provides an interface to TerraLib geographical database, allowing models direct access to geospatial data.

VisualBots	**Academic-basic**	**Updated: 2008**

http://www.visualbots.com/index.htm
VisualBots for Excel is an educational tool for exploring the fascinating world of multi-agent systems and their emergent behaviors. The VisualBots simulator can be used to create virtual worlds of programmable agents that interact with one another through time.

ZEUS	**Commercial**	**Updated: 2013**

https://sourceforge.net/projects/zeusagent/
Zeus provides a graphical environment to build distributed agent systems. A rule engine, planner and visualization tools are included.

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Appendix B. Sampling of Computational Social Science Society of the Americas (CSSSA) Conference Papers

Fifty-four papers submitted to the CSSSA serve as a sample from which to extrapolate the nature of public research applicable to Human Domain elements. Papers were published throughout the last 3 CSSSA conferences (2012, 2013, and 2015).

1. Lauf T, Gawel E, Frank K. The spatial allocation of renewable power infrastructure–an economic assessment of energy landscapes with an agent-based modelling approach; 2015.
2. Clark R, Kimbrough SO. The spontaneous emergence of language variation from a homogeneous population; 2015.
3. Bodo P. How much abuse can markets take? on the structural effects corporate income redistribution; 2015.
4. Baseman E, Jensen D. Exploring collective behavior in social computation through relational statistical models; 2015.
5. Gulden T, Koehler M, Scott S, Henscheid Z. Evidence for allometric scaling of government services in American cities; 2015.
6. Sakahira F, Terano T. Generating anthropological and archaeological hypotheses in Okinawa through agent-based simulation; 2015.
7. Sandoval-Felix J, Castanon-Puga M, Gaxiola-Pacheco C. Using an urban growth simulator for Ensenada city public policy analysis; 2015.
8. Dixon D, Stith S, An agent-based model of innovation in organ transplant data; 2015.
9. Garibay I, Akbas MI, Gunaratne C, Ozmen O, O’Neal T. An agent-based approach to study incubation in innovation ecosystems; 2015.
10. Barkoczi D, Galesic M. Social learning strategies, network structure and the exploration-exploitation tradeoff; 2015.
11. Aydogmus O, Çagatay H, Gurpinar E, Oguz F. The effect of expertise in norm formation; 2015.
12. Bassett J, Cioffi C. Evolutionary computation applied to agent-based simulation modeling of climate and social dynamics; 2015.
13. Oviedo L, Koehler M, Taylor M. Exploring organizational learning and structuring; 2015.

14. Michel S, Megerdoomian K. Modeling community resilience for a post-epidemic society; 2015.

15. Yang Z. An agent-based dynamic model of politics, fertility and economic development; 2015.

16. Gonnering R, Lein J. Political speech: poem, preaching, performance? a pilot computational study; 2015.

17. Carbone G, Giannoccaro I. Collective decision making on complex landscapes; 2015.

18. Leibzon W. Modeling competitive beliefs on social network; 2015.

19. Adiga A, Chu S, Marathe A, Vullikanti A. Behavioral modeling for epidemic planning and response; 2015.

20. Henderson H. Modern value chains and the organization of agrarian production; 2015.

21. Taghawi-Nejad D. An agent-based model to understand the effect of interactions between federal, state and local governance on the distribution of educational resources; 2015.

22. Abdollahian M, Yang Z, Coan T, Yesilda B. Human development dynamics: an agent-based simulation of social systems and heterogeneous evolutionary games; 2013.

23. Baggio JA. Synchronization of management strategies; 2013.

24. Bloomquist KM, Koehler M. A large-scale agent-based model of taxpayer reporting compliance; 2013.

25. Bramson A, Grim P, Singer DJ, Fisher S, Sack G, Berger W, Flocken C. Measures of polarization and diversity; 2013.

26. Dixon DS, Mozumder P, Vásquez WF. An information entropy approach to salience for survey-driven simulation; 2013.

27. Duong D. The data absorption technique: coevolution to automate the accurate representation of social structure; 2013

28. Galloway E, Mappus RL IV, Briscoe E. The role of networks in durable goods technology adoption; 2013.

29. Garibay I, Hollander CD, Ozmen O, O'Neal T. Towards modeling economic ecosystems: an initial model and preliminary validation; 2013.

30. Ge J. Endogenous formation and collapse of housing bubbles; 2013.

31. Golman R, Hagmann D, Miller J. Polya's bees: decentralized decision making with quorum-based strategies; 2013.

32. Herrmann J, Rand W, Schein B, Vodopivec N. An agent-based model of urgent diffusion in social media; 2013.

33. Kennedy WG, Harrison JF. Towards representing disasters in computational social simulations; 2013.

34. Kim Y. Dynamics of the silence of majority from the perspective of social dilemma; 2013.

35. Krejci CC, Beamon BM. Modeling the impacts of farmer coordination on food supply chain structure; 2013.

36. McCaskill JR. Complex humanitarian intervention simulation; 2013.

37. Nasrallah WF, Cheaib KA, Yassine AA. A dynamic equilibrium model of how regulative and normative institutions influence economic behavior and growth; 2013.

38. Waring TM, Goff S, Smaldino PE. Evolving the core design principles: the coevolution of institutions and sustainable practices; 2013.

39. Zhang H, Putra HC, Andrews CJ. Modeling real estate market responses to climate change in the coastal zone; 2013.

40. Flocken C, Carmichael T, Hadzikadic M. The role of uninformed individuals in making the right group decisions; 2012.

41. Geller A, Latek M, Rizi SMM, Fournier S, Prenot-Guinard F. Contexts as reasoning and action frames for multi-agent societies; 2012.

42. Gonnering RS. Modeling the spread of a "cultural meme" through an organization; 2012.

43. Griffin WA, Li X. Unsupervised learning of dyadic processes: models, methods, and simulation; 2012.

44. Gulden T. Modeling selective violence in the Guatemalan civil war; 2012.

45. Hagmann D, Tassier T. Spatial coordination games with agent turnover; 2012.

46. Hailegiorgis A, Crooks AT. Agent-based modeling for humanitarian issues: disease and refugee camps; 2012.

47. Latek MM, Rizi SMM, Crooks AT, Fraser M. A spatial multi-agent model of border security for the Arizona–Sonora borderland; 2012.

48. Lawless WF. Incompleteness, uncertainty and autonomy: intelligent systems; 2012.

49. Mappus RL IV, Briscoe E, Hutto CJ. Effects of exogenous input on adoption rates in social networks; 2012.

50. Marlin B, Sohn H. Demand based balance of flow manpower modeling for education policy in Afghanistan; 2012.

51. Parunak HVD, Brooks HS, Brueckner S, Gupta R. Dynamically tracking the real world in a CSS model; 2012.

52. Schoon M, Baggio J, Salau K, Janssen M. Modeling decision-making across habitat patches: insights on large-scale conservation management; 2012.

53. Wise S, Scott S. The puck stops here: evolving social norms of helmet usage in the National Hockey League; 2012.

54. Yang Z, Abdollahian M, Nelson H, Close B. Getting to yes: the sustainable energy modeling project (SEMPro) model of infrastructure siting; 2012.

List of Symbols, Abbreviations, and Acronyms

2-D	2-dimensional
3-D	3-dimensional
ABM	agent-based modeling
ACT-R	adaptive control of thought–rational (often refers to a cognitive architecture)
API	application program interface
ARSOF	Army Special Operations Forces
ASCOPE	area, structures, capabilities, organizations, people, and events
BCT	brigade combat team
CADSIM	COA Analysis by Integration of Decision and Social Influence Modeling with Multi-Agent System
CGSC	Command and General Staff College
CM2E	complex military mission environment
COA	course of action
COEM	complex operational environment model
COIC	Counter-IED Operations/Intelligence Center
COIN	counterinsurgency operations
COMPOEX	Conflict Modeling, Planning, and Outcomes Experimentation Program
CRA	Charles River Analytics
CSSSA	Computational Social Science Society of the Americas
DA	Department of the Army
DARPA	Defense Advanced Research Projects Agency
DCGS-A	Distributed Common Ground System–Army
DIME	diplomatic, information, military, and economic

DIME-FIL	diplomatic, information, military, economic, financial, intelligence, and law enforcement
DSTL	Defence Science and Technology Laboratory, Ministry of Defence, United Kingdom
FAO	Foreign Area Officer
GAMA	agent-based modeling framework
GIS	geographical information system
GIT	version control system
GROWlab	Geographical Research on War Laboratory
HIG	Hezb-e Islami Gulbuddin
HQ	Headquarters
HSCB	Human Social Culture Behavior
ID	identification
IED	improvised explosive device
IPB	intelligence preparation of the battlefield
IW	irregular warfare
IW TWG	irregular warfare tactical wargame
JDL	Joint Directors of Laboratories, often refers to the JDL data fusion model
JFCOM	Joint Forces Command
JIEDDO	Joint Improvised Threat Defeat Agency
JIPOE	Joint Intelligence Preparation of the Operational Environment
JNEM	Joint Non-Kinetic Effects Model
JPL	Jet Propulsion Laboratory
JTF	joint task force
JWARS	Joint Warfare Systems
KSA	knowledge, skills, and abilities

LOA	level of automation
MDMP	military decision-making process
METT-TC	mission, enemy, terrain, troops available, time, and civilian considerations
MISO	military information support operations
NOEM	national operational environment model
NTC	National Training Center
OAKOC	Observation and fields of fire, Avenues of approach, Key and decisive terrain, Obstacles, Cover and concealment
OneSAF	One Semi-Automated Force
OODA	observe, orient, decide, and act
ORSA	Operations Research and Systems Analysis
PMESII	political, military, economic, social, information, and infrastructure
PMESII-PT	political, military, economic, social, information, infrastructure, physical environment, and time
PSOM	peace support operation model
RAND	American nonprofit global policy think tank
RebeLand	an agent-based model built upon the MASON agent-based framework
RFI	Request for Information
RWISE	reference world information and simulation environment
S&T	Science and Technology
SAF	semi automated force
SEAS	synthetic environment for analysis and simulation
SME	subject matter expert
SOAR	state, operator and result (often refers to a cognitive architecture)
SOCOM	Special Operations Command

TRADOC	US Army Training and Doctrine Command
UK	United Kingdom
vmStrat	Versatile Multiscale Strategist
V-SAFT	virtual strategic analysis and forecasting tool
W-ICEWS	worldwide-integrated crisis early warning system
XO	Executive Officer

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
2 (PDF)	DIRECTOR US ARMY RESEARCH LAB RDRL CIO L IMAL HRA MAIL & RECORDS MGMT
1 (PDF)	GOVT PRINTG OFC A MALHOTRA
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